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An experimental approach to unravel 2D ground resonances: application to an alluvial-sedimentary basin

Giulia Sgattoni[1,2*], Giovanni Lattanzi[2] and Silvia Castellaro[2]

Abstract

The study of ground resonances is important to assess seismic site amplification and to infer information on the geometrical and mechanical properties of the resonating structures. 1D- and 2D-type resonances imply different dynamic behavior that can be distinguished by inspecting the individual spectral components of single-station microtremor measurements. Typically, 2D resonance modes develop along cross-sections of deep sediment-filled valleys and consist of longitudinal, transverse and vertical modes that can be identified as spectral peaks when ground motion is recorded parallel to the axes of the valley. In the case of more complex geometries, such as sedimentary basins, resonance modes are more difficult to predict and depend on the unknown complexity of the buried bedrock geometry. We show how a simple signal rotation procedure applied to single-station microtremor recordings reveals the underlying 2D resonance pattern. The method allows assessing the axes of motion of buried geological structures and identifying 2D resonance modes along these axes. Their directionality, frequency and amplitude features are then analyzed to extract information on the bedrock geometry. We test our method in the Bolzano alluvial-sedimentary basin and we observe that apparently complicated resonance patterns may be simplified by locally referring to the simplest description of the phenomenon as 2D resonance of a valley slice. The bedrock morphology can be decomposed into 2D-like geometries, i.e., excavated channels, and the observed resonances develop within cross-sections of these channels.

Keywords Site effects, Vibration modes of sedimentary basins, 2D resonance, Directional analysis, Single-station microtremor measurements

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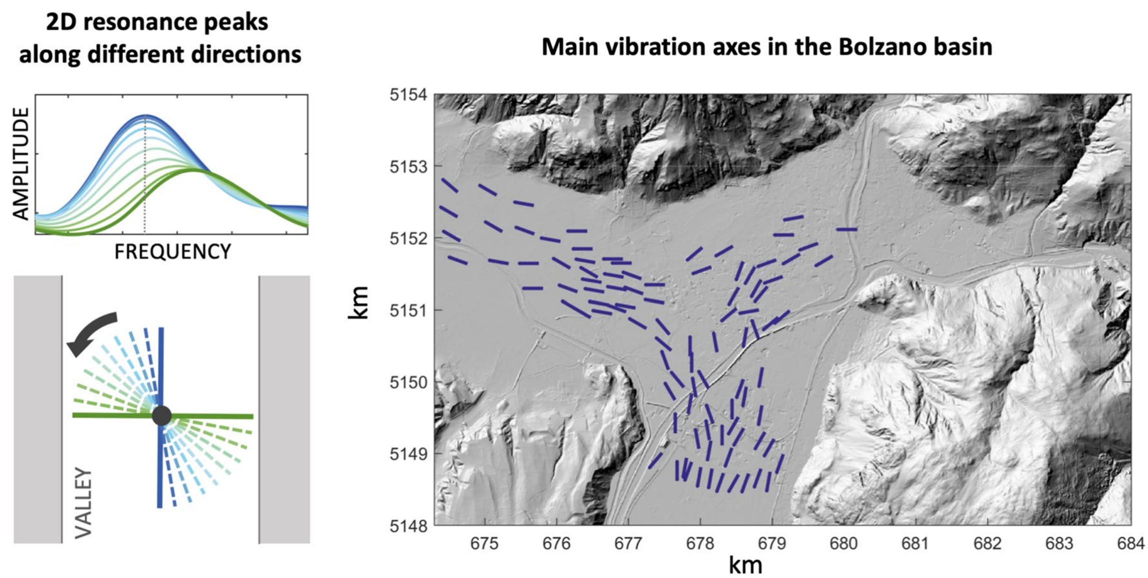
Graphical Abstract



Introduction

Resonances of seismic waves trapped in sedimentary layers can significantly amplify ground motion. Measuring them is important for seismic site amplification studies and to infer some mechanical properties of the resonating geological body. It is common to approach the study of ground resonances under a 1D assumption, i.e., a plane-parallel stratigraphy. The task is usually addressed by means of the *H/V* (horizontal to vertical spectral ratio, Nakamura 1989) technique, that allows the identification of ground resonances as peaks on the *H/V* curve recorded at a site (see Molnar et al. 2022 for a review on the technique). In the simplest case of a horizontal sediment layer overlying a bedrock half-space, 1D resonance frequency is inversely linked to the local bedrock depth, as a function of the shear wave velocity of the sediment layer. Therefore, when the 1D approximation holds locally, spatial variations of the 1D frequency reflect changes of bedrock depth (when lateral homogeneity of the sediment cover can be assumed).

The 1D approximation is not sufficient at sites with narrow aspect ratios compared to the wavelengths of interest. Several authors have investigated the 2D dynamic behavior of sediment-filled valleys both numerically (e.g., King and Tucker 1984; Bard and Bouchon 1980a, 1980b, 1985; Moczo et al. 1996; Steimen et al. 2003; Frischknecht and Wagner 2004) and experimentally (e.g., Roten et al. 2006; Le Roux et al. 2012; Ermert et al. 2014; Sgattoni and Castellaro 2020). Geological structures with different geometrical or stiffness properties along two main axes, such as sediment-filled basins, have a different dynamic behavior along the two directions. These can be identified as peaks with different frequency in the horizontal spectral components of motion recorded along these directions, even with a single-station microtremor approach (Fig. 1; Sgattoni and Castellaro 2020). These peaks correspond to the 2D longitudinal (*L*) and transverse (*T*) resonance modes developing within a valley cross-section (Fig. 1a), that vibrates simultaneously at the same frequencies. These correspond to the SH and SV modes described by previous authors (e.g., Bard and Bouchon 1985; Roten et al. 2006; Le Roux et al. 2012; Ermert et al. 2014), that we name longitudinal and transverse modes to depict the direction of motion with respect to the valley axis.

Differently from the 1D case, 2D resonances can no longer be linked to the local stratigraphy directly below the measurement site, but depend on the whole valley geometry and mechanic properties that can be assessed referring to specific models. Some relations exist to relate 2D transverse and longitudinal frequencies to the valley width and maximum depth and to the theoretical 1D frequency at the site of maximum bedrock depth. There is also a direct correlation between the *T*/*L* frequency ratio and the aspect ratio of the valley under specific hypotheses (e.g., Bard and Bouchon 1980a,b; Rial 1989; Sgattoni and Castellaro 2020).

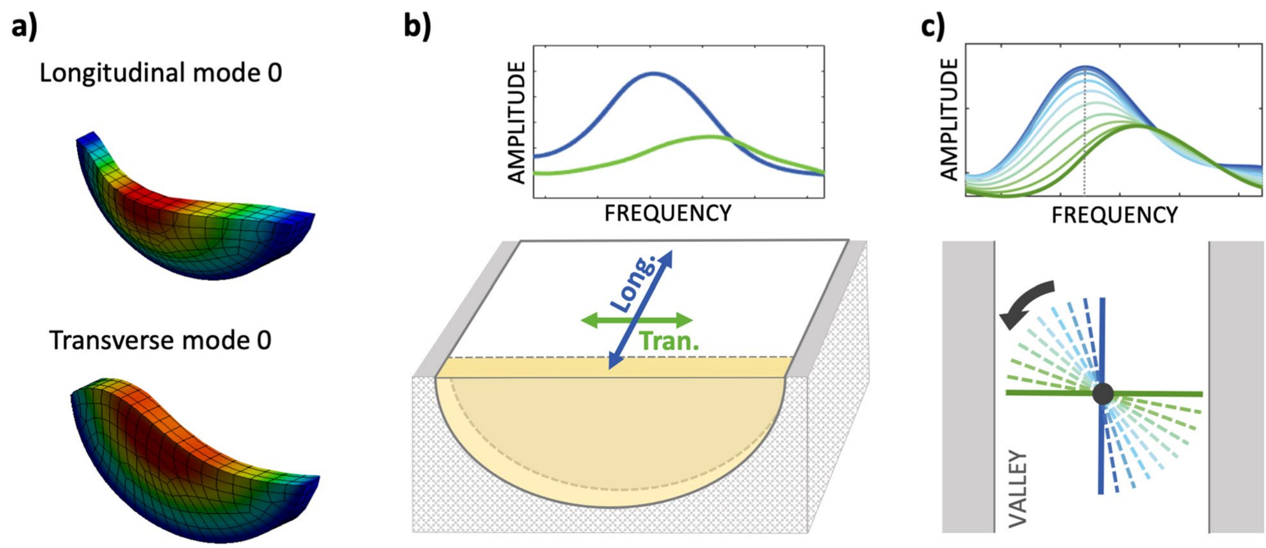


Fig. 1. 2D resonance modes along a cross-section of a sediment-filled valley. **a** Fundamental longitudinal (L_0) and transverse (T_0) mode shapes of a valley slice (ideally corresponding to the yellow volume in **b**). Red colors indicate the maximum displacement, which has a horizontal component only in the longitudinal mode and both a horizontal and a vertical component in the transverse mode. **b** Resonance peaks corresponding to the L_0 and T_0 modes, recorded along the longitudinal and transverse directions of a valley. **c** Amplitude spectra of motion recorded along different directions with rotations between 0 and 90 degrees with respect to the longitudinal direction of the valley. The grey line indicates the position of the peak identifying L_0

The fundamental longitudinal (L_0) and transverse (T_0) modes are easiest to identify in practice, as they are typically higher in amplitude, at least when excited. L_0 mode is characterized by lower frequency than T_0 and, usually, by higher displacement amplitude (Fig. 1a; Roten et al. 2006; Le Roux et al. 2012; Ermert et al. 2014). In some cases, higher vibration modes can also be observed, although their identification is not straightforward. The T_0 mode is also associated to a vertical component (Fig. 1a). L_0 and T_0 mode shapes at the free surface are somehow linked to the bedrock geometry. For a symmetrical valley cross-section with homogeneous sediment fill, they are characterized by maximum horizontal displacement in the valley center (where the sediment thickness is maximum) and tend to zero towards the edges (Bard and Bouchon 1980a,b; Ermert et al. 2014; Suzuki et al. 2021).

All the mentioned studies analyzed truly 2D conditions, i.e., valleys with fixed cross-section geometry and infinite length. In the simple case of a sediment-filled valley with constant cross-section along its longitudinal axis, 2D resonances develop, with the same characteristics, along any cross-sections of the sediment fill. This implies that the whole sediment fill of the valley vibrates simultaneously at the same 2D eigen frequencies, that do not vary neither along the valley cross-section, nor along the valley axis. We can therefore expect that, for example, changes of the valley cross-section along its axis will determine changes in the 2D resonance patterns. In the case of a sedimentary basin, such patterns are more difficult to predict and depend on the unknown complexity of the bedrock geometry. Few authors have studied 3D resonances of simplified basins theoretically and by modelling 3D effects on H/V functions (e.g., Rial 1989; Guillier et al. 2006).

In this study, we attempt to unravel resonance patterns in a sedimentary basin with an experimental investigation of single-station microtremor recordings. We use the term 'resonance patterns' to indicate the spatial characteristics of ground resonances in terms of frequencies, directionality and amplitude. We base our analysis on the physical description of 2D resonances shown in Fig. 1 and perform a directional analysis of ambient noise recordings to investigate the directivity of observed ground resonances. Previous studies on the directivity of ambient noise used different techniques. Particle motion polarization methods (Vidale 1986; Jurkevics 1988) were applied by, e.g., Ermert et al. (2014) and Del Gaudio (2017) to investigate the directivity of site resonances, by Burjánek et al. (2010) to investigate directional effects on an unstable mountain slope, by Burjánek et al. (2014) to investigate directional topographic effects. These analyses provide directional information in both horizontal and vertical planes; however, they require long-duration acquisitions to obtain stable results on seismic microtremor and often involve signal filtering. *F-k* analysis and frequency domain decomposition methods require array measurements and were applied by Roten et al. (2006) and Ermert et al. (2014) to investigate 2D resonance directionality. A simpler approach used to investigate ground resonance directivity is the computation of azimuthal variation of single-station H/V ratios (e.g., Di Giulio et al. 2009; Panzera et al. 2014). This involves mixing the components of motion, which instead should be treated independently when investigating vibration modes. We propose an approach based on the analysis of the azimuthal variation of individual horizontal spectral components of motion recorded at a single site. The method is based on the same processing needed for H/V analysis and can be applied to a large number of short-duration single-station measurements. It allows the identification of the main axes of motion at each measurement site and their corresponding frequencies and amplitudes. Our approach is partly similar to the directional analysis by Matsushima et al. (2017), which is applied to the N/V and E/V ratios. However, in the directional analysis of 2D resonances the ratio with the vertical component is not recommended as it mixes up the resonance modes that include both horizontal and vertical components.

We test our approach on the Bolzano alluvial-sedimentary basin (Northern Italy), that lies at the intersection of three valleys. We analyze a set of 300 single-station microtremor measurements covering the whole basin and investigate the directionality, frequency and amplitude features of the observed resonance modes. We observe that these features carry useful information on the bedrock geometry and that apparently complicated resonance patterns can be simplified by locally referring to the simplest description of the phenomenon as 2D resonance of a valley slice (i.e., the case shown in Fig. 1). This study follows the analysis presented in Sgattoni and Castellaro (2020) where part of the same data is presented and the criteria to discern 1D and 2D resonances are described in detail along three profiles across the basin. The same criteria are applied in the present study to a larger dataset covering the whole basin to identify all sites dominated by 2D resonances and investigate their directional behavior. We then compare our results with the 3D bedrock model obtained by Sgattoni and Castellaro (2021) from joint modelling of microtremor and gravity measurements.

Methods

We start our analysis by visually identifying 2D resonance peaks on the individual spectral components of motion at all investigated sites. These can be distinguished from (and can coexist with) 1D-type resonances based on the features of the 3 component amplitude spectra described by Sgattoni and Castellaro (2020): the 2D resonance is identified by two peaks at different frequencies along the horizontal spectral components of motion while in the case of 1D resonance the horizontal spectra coincide and usually a local minimum in the vertical spectral component is observed.

For our analysis of the L_0 and T_0 modes, we focus on the spectra of the horizontal components of motion. The vertical component is only used for amplitude analysis as explained later in this section. The L_0 and T_0 modes occur at different frequencies along the longitudinal and transverse direction of the resonating structure with $f_{LONG\_0} < f_{TRAN\_0}$. This is observed when ground motion is recorded parallel to these directions and in this condition also the observed L_0 and T_0 spectral amplitudes are maximum. Rotating one motion component from a direction parallel to the longitudinal axis to a direction perpendicular to it determines what is illustrated in Fig. 1c: the resonance peak initially identifies the L_0 mode (dark blue line) then gradually decreases in amplitude and moves to higher frequency until reaching the transverse direction identifying the T_0 mode (dark green line). The L_0 mode is identified by the peak at the lowest frequency and acts along the orientation where the peak amplitude is maximum. When the best orientation is not known in advance, this can be searched by performing such rotation of the recorded ground motion.

To do this, we apply the following procedure to a set of single-station microtremor measurements:

a) Compute amplitude spectra of the original signals and identify the 2D resonance peaks on the horizontal spectral components. These are the projections of the real 2D modal frequencies along the axes chosen for the measurements on the field (that we call instrumental components, x and y; Fig. 2a).
b) Rotate all recorded signals around the vertical axis, with 10-degree resolution up to 80° from the initial directions of the instrumental components and obtain the horizontal spectra of each rotated signal (Fig. 2b). The choice of the 10-degree resolution depends on the estimated uncertainty in the instrument positioning; however, the analysis can be done with a smaller angle step.
c) Extract the frequency values of the spectral peaks along the instrumental x and y components (f_x and f_y) and identify the orientation(s) that maximizes the modulus of frequency difference for each rotation angle θ (Fig. 2b):

$$\Delta f_{\theta} = |f_x - f_y| \quad (1)$$

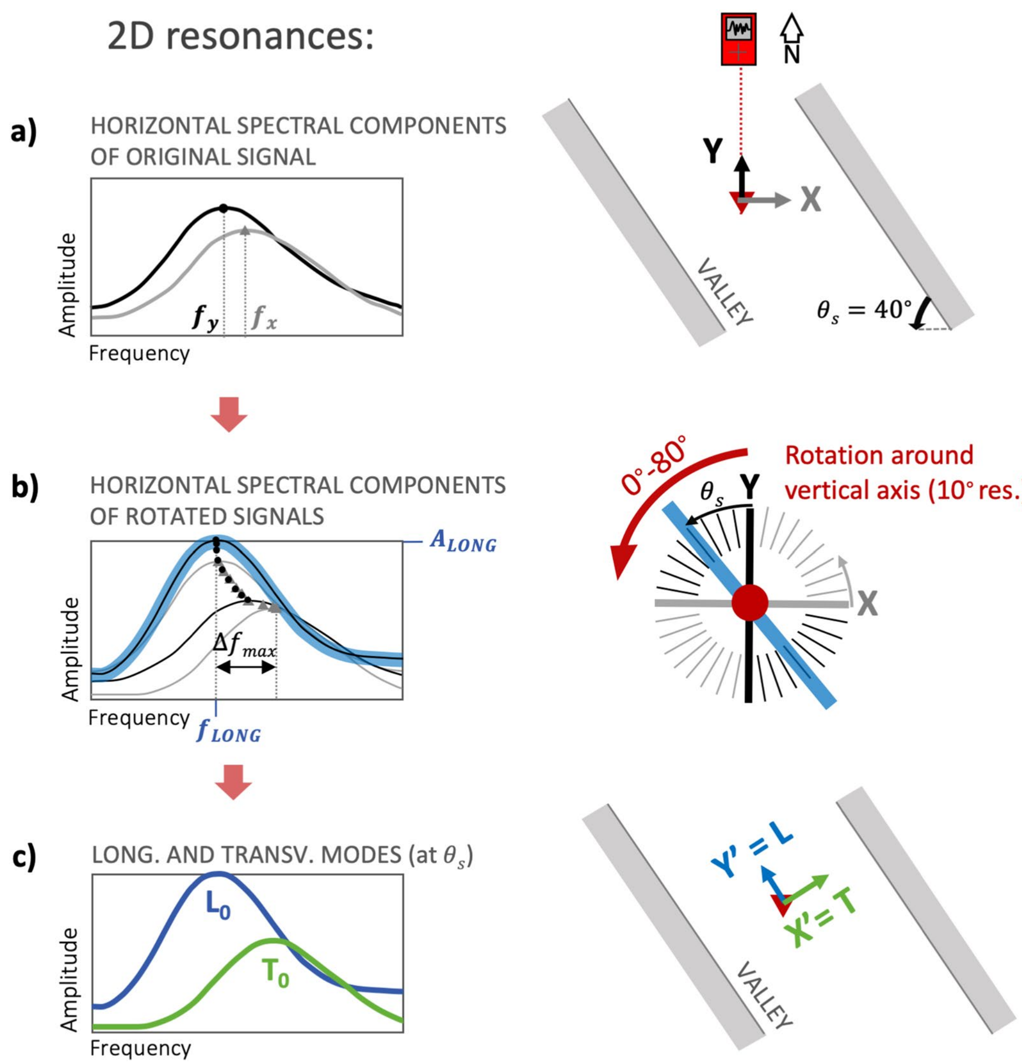


Fig. 2 Assessment of the principal axes of motion of a hypothetical valley with axis oriented 40°N. **a** Observed resonance peaks along instrumental *x* and *y* components (grey and black, respectively, with the peaks marked by a black dot and a grey triangle) corresponding to the acquisition configuration drawn on the right (with *y* component parallel to geographic North). These correspond to the projections of the principal axes of motion of the valley. **b** *x* and *y* spectral components of signal rotated counterclockwise around the vertical axis between 0 and 80 degrees, with 10 degrees resolution. The rotation determines that the peaks along the *x* direction move within the area bounded by grey curves with the peaks marked by the grey triangles, while the *y* spectral peaks move within the area bounded by black curves with the peaks marked by the black dots. The thick blue line highlights the peak with lowest frequency and highest amplitude, i.e., the fundamental vibration mode along the longitudinal direction (blue direction on the polar plot), at the rotation angle θ_s. **c** L_0 and T_0 modes along the real longitudinal and transverse direction of the valley

More than one rotation angle may be found that meets this condition, depending, e.g., on the spectral resolution of the signal. For this reason, also steps d and e are necessary to identify a unique solution.

d) Extract the minimum frequency between f_x and f_y at the rotation angles maximizing Eq. 1. This frequency identifies the L_0 mode (f_{LONG}; Fig. 2b).
e) Search for the rotation angle θ_s that maximizes the amplitude at the L_0 frequency, called A_{LONG} (blue curve in Fig. 2b). Because the signal is rotated within 80° only, the maximum value of A_{LONG} might be found in the x or y direction. Assuming that the instrumental y direction is initially parallel to the geographic North direction, if the maximum L_0 amplitude is found along y as in Fig. 2b, then the longitudinal direction is θ_s degrees from the geographical North, otherwise it is $\theta_s + 90$.

In other words, with this procedure we project the instrumental components along all horizontal directions (Fig. 2b) and choose as principal directions the ones that maximize the amplitude spectrum at the resonance frequency and the frequency distance between L_0 and T_0. This provides the optimal rotation angle to assess the local longitudinal and transverse directions of a valley slice and the fundamental frequencies of the L_0 and T_0 modes (Fig. 2c).

We note that the relative amplitudes of the L_0 and T_0 modes might not be always as in Fig. 2c, with $A_{\mathrm{LONG}} > A_{\mathrm{TRAN}}$. However, the proposed procedure works also if $A_{\mathrm{LONG}} < A_{\mathrm{TRAN}}$ since it is first based on the frequency difference between the two modes.

We then focus on L_0 for further analysis on the frequency and amplitude pattern across the basin. Once the horizontal optimal rotation angles are identified, we analyze amplitudes in terms of $A_{\mathrm{LONG}}/A_{\mathrm{VERT}}$ ratio, where the ratio is meant to clear source effects as for the H/V ratio. This approach is acceptable since the longitudinal motion in a valley is not expected to have an associated vertical component.

Single-station microtremor data in the Bolzano sedimentary basin

Data acquisition and processing

We acquired single-station microtremor measurements at 300 sites within the Bolzano alluvial-sedimentary basin (red dots in Fig. 3), which lies at the intersection between the Adige, Sarentino and Isarco valleys (Fig. 3). This is an alluvial-sedimentary basin made of fine- to coarse-grained fluvioglacial and lacustrine quaternary deposits. The sediment fill lies on a Permian porphyritic bedrock.

Ground motion recordings were acquired with Tromino seismometers (MoHo srl) at 128 Hz sampling rate and lasted 16 min. For all measurements we used two Tromino® 3G 3-component portable velocity/acceleration sensors by MoHo srl (Italy), after checking that their response was identical. These instruments have a self-noise of about $2{*}10^{-7}$ m/s at the frequencies of interest in this study ($\cong$0.3 Hz) and were set to have a resolution of $6{*}10^{-11}$ m/s in the $\pm$0.5 mm/s range.

Instruments were always oriented with the y and x components parallel to the geographical NS and EW directions. These measurements are part of a larger dataset, acquired in a wider area over a 2-year time range, which included also longer duration acquisitions in a few test sites (up to 1.5 h).

To compute individual spectral components, each waveform was split into 30 s non-overlapping windows,

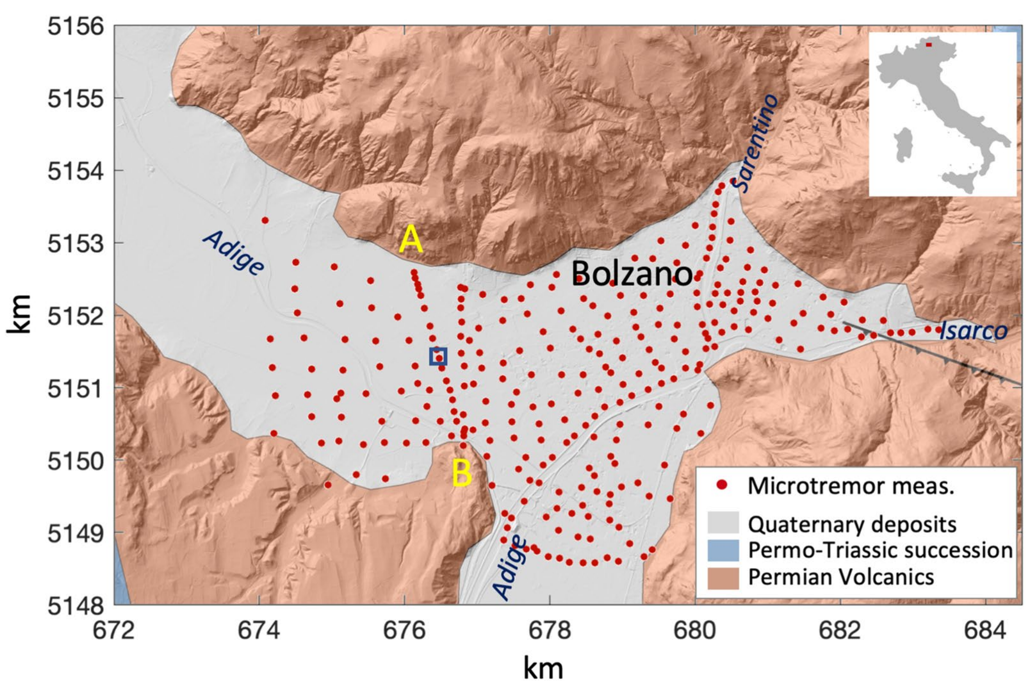


Fig. 3 Geologic map of the Bolzano alluvial-sedimentary basin and locations of the single-station microtremor measurements. The blue square indicates the location of the measurements shown in Fig. 4. Geologic data from Keim et al. (2013). Letters A and B identify the line along which the data shown in Fig. 5 were acquired. Geologic data from Keim et al. (2013)

detrended, tapered, padded, FFT-transformed and smoothed with triangular function with width equal to 5% of the central frequency. We used a narrow smoothing function to improve the identification of the resonance peaks. From the individual spectral components, we also obtained the H/V curves by averaging the H/V ratios computed for each window, H being computed as $\sqrt{x^2 + y^2}$. The use of H/V curves is not necessary to identify 2D vibration modes, however, it can help in the preliminary analysis to identify resonance frequencies at the different sites and to distinguish 1D and 2D conditions.

The duration of the acquired signals was chosen to optimize acquisition times while being able to resolve spectral frequencies down to 0.2 Hz. This is crucial as our analysis requires covering the basin with as many measurements as possible and, in general, investigating a large number of sites is useful, if not necessary, to interpret the observed patterns. The trade-off between measurement duration and number of points was also influenced by the use of two instruments that had to be guarded during the measurement. A 16-min recording contains 32 non-overlapping windows of 30 s, which allow good spectral reconstruction down to 0.13 Hz (corresponding to one-fourth of the signal length). After manual removal of transients, a portion usually around 10–20% of each signal was removed, which saves a minimum of 25 windows. This is enough for the statistical significance of the resulting averaged spectrum (SESAME 2004). Bad quality data (with transients affecting more than 40% of the windows) were discarded. These were usually associated to local disturbances (especially for acquisitions in industrial or urban areas) and/or wind gusts.

We also tested the statistical significance and stability of our spectral analysis by acquiring a few microtremor measurements at the same sites during different times and with different acquisition durations. An example is reported in Fig. 4, where the spectra of two recordings acquired in different seasons and with different durations (16 and 60 min) are compared. Both measurements were analyzed by splitting the signal into 30 s and 60 s windows. In all cases, the spectral peaks on the horizontal components can be identified at the same frequencies. The use of a longer window ensures better spectral resolution that improves accuracy of the frequency estimation, however, for short acquisition lengths this would reduce the number of windows. In addition, the 300 measurements were acquired in different seasons in a time-range of 2 years, mostly under good weather conditions, and we observed always stable patterns.

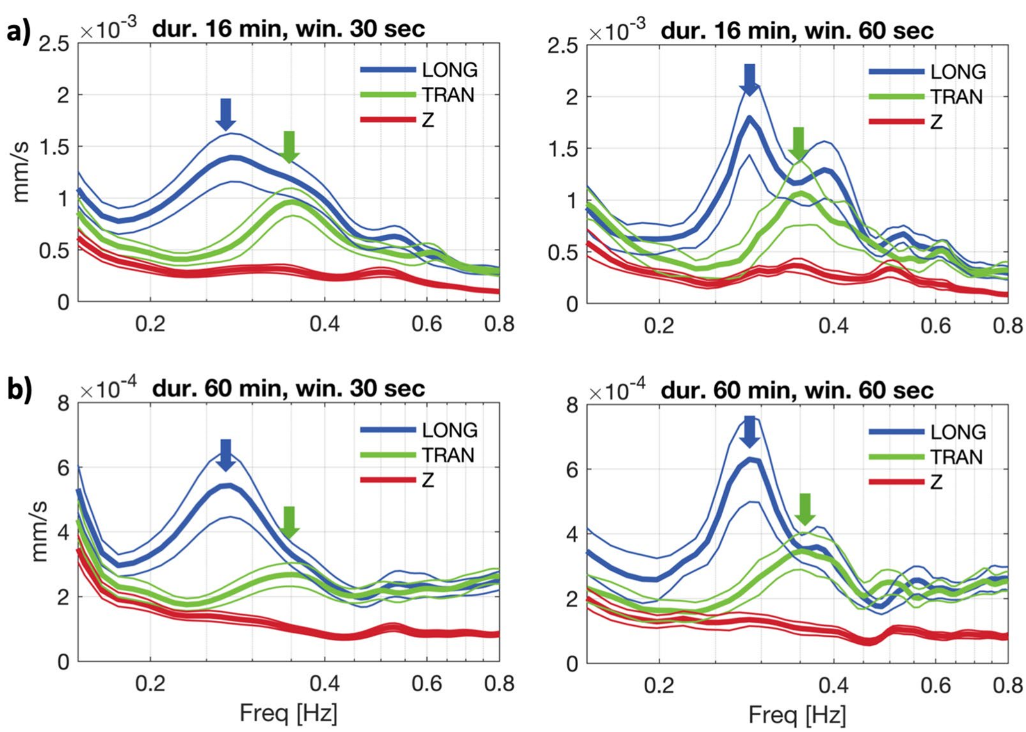


Fig. 4 Effect of different acquisition and processing strategies. **a** 16-min recording acquired in February 2019; **b** 60-min recording acquired in July 2019. Both measurements were acquired at the site indicated in Fig. 3. The thin lines correspond to the confidence interval

Identification of 2D resonance peaks on individual amplitude spectra

We identified the 'presumed' 2D vibration modes as spectral peaks on the horizontal spectral components occurring at frequencies ranging between 0.27 and 0.53 Hz. We call them 'presumed' because they could be a projection of the principal main vibration directions, depending on the instrumental orientation at the site, compared to the valley axes. The identification of 2D spectral peaks is easier when the data are viewed along lines crossing the valleys, as in Fig. 5 where H/V curves (Fig. 5a) and corresponding individual spectral components acquired along line A–B of Fig. 3 are shown. Because we are interested in the vibration modes of the whole sediment fill, we point our attention to the lowest observed resonance frequencies, discarding higher resonances due to internal layering of the sediment fill. Distinct peaks along the instrumental x and y spectral components are clearly observed at low frequencies (within the red rectangle in Fig. 5b). Their amplitude is maximum close to the center of the valley and they disappear on the sides (Fig. 5b, c). This is expected, since modal amplitudes decay towards

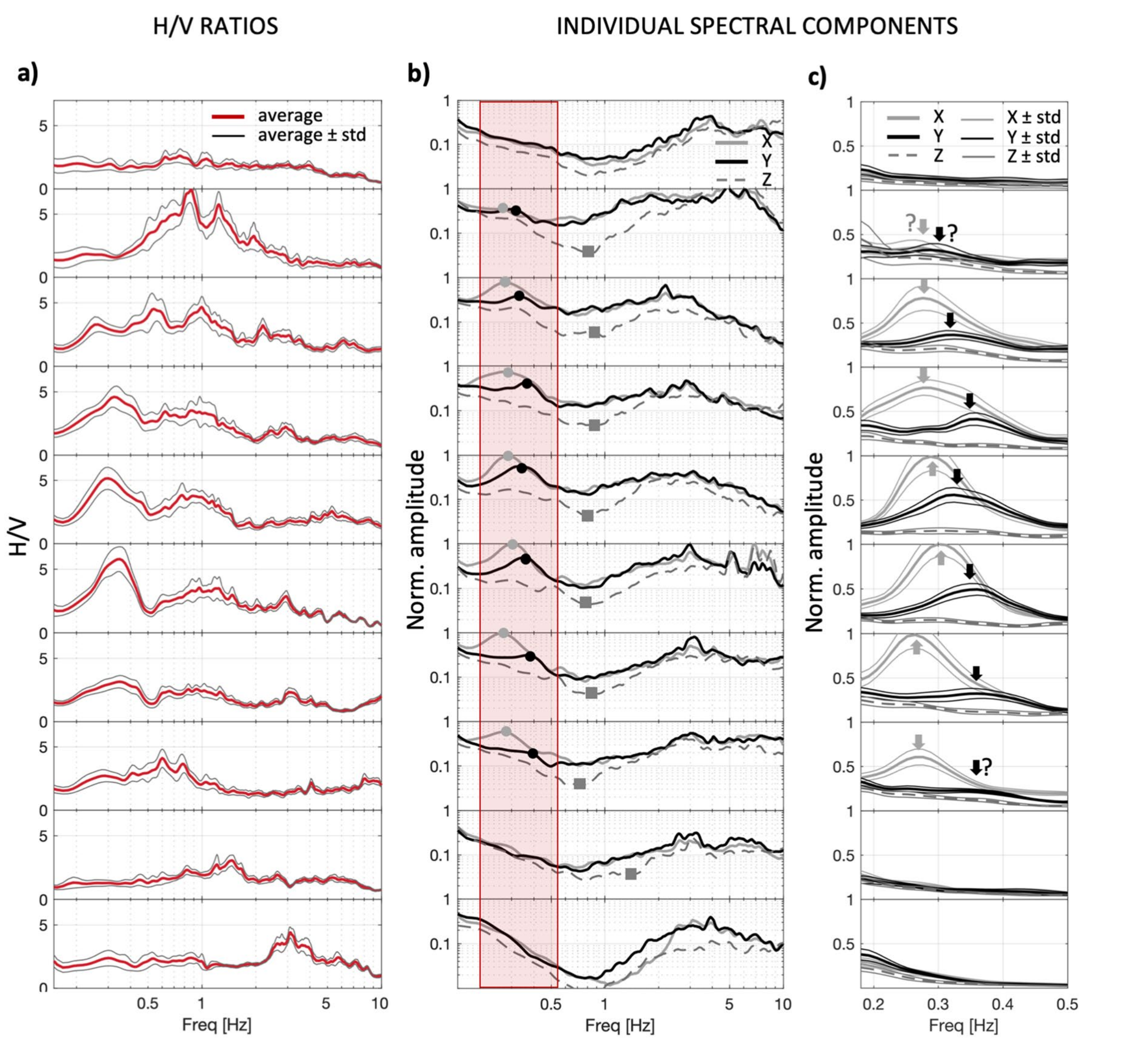


Fig. 5 Examples of single-station microtremor measurements acquired along line A–B (top to bottom) in Fig. 3. **a** *H/V* ratios and their confidence interval. **b** Individual spectral components of motion in logarithmic scale. The red rectangle highlights the frequencies where 2D resonance peaks are observed and corresponds to the zoomed plot in **c**). The grey and black circles mark the 2D resonance peaks on the *x* and *y* instrumental components, while the grey square marks the minimum on the vertical spectral components at the 1D resonance frequency. **c** Plot of individual spectral components and their confidence interval zoomed around the presumed 2D resonance modes marked by arrows. Amplitudes are normalized with respect to the absolute maximum peak amplitude within the red box to better appreciate their decay towards the valley edges

the valley edges. This determines that the 2D vibration modes are observed mainly in the central parts of the basin and valleys (Fig. 6). The use of a linear scale helps identifying the 2D resonance peaks (arrows in Fig. 5c). We note that the vertical component associated to the 2D transverse modes is only locally observed in our data. In this respect, we note that in general the amplitude of the horizontal components tends to be larger than the vertical component in the whole frequency range, and that the vertical component of the transverse mode should be observed close to the edge of the valley (and has ideally zero amplitude at the valley center; e.g., Ermert et al. 2014) where the mode amplitudes are very weak.

For our investigation of 2D resonance modes it is enough to focus on the individual spectral components, however, we show also the H/V ratios for comparison and because they are useful to identify and laterally correlate ground resonances between different sites with different 1D/2D dynamic properties. The H/V ratios in Fig. 5a contain peaks that are sometimes due to the 2D maxima on the horizontal components (circles in Fig. 5b) and sometimes to local troughs in the vertical component (squares in Fig. 5b), a feature related to laterally propagating surface waves in a 1D-like site. We note that in some cases both 1D and 2D resonances are observed at the same site and that 2D resonances are not always accompanied by clear peaks on the H/V curve, an additional reason why 2D resonances should be looked for in the individual spectra. At the sites where 2D resonance peaks are not observed, either flat H/V curves are recorded or 1D resonances identified with peaks on the H/V functions (see Sgattoni and Castellaro 2020 for further details). Flat H/V curves in this context do not necessarily implicate the absence of resonance, but are rather sites where 2D modes are weak (e.g., close to the valley edges).

2D resonance peaks were identified at 101 sites distributed mainly along the Adige valley and in the central part of basin (as denoted by red circles in Fig. 6). At the rest of the sites we observed 1D resonances (e.g., in the eastern part of the basin and in the western part south of the Adige river) or unclear/absent resonance peaks. The spatial distribution of 1D/2D resonances is likely related to the bedrock morphology, with 1D resonances occurring in the shallower parts of the basin. We also note that at a few points close to the center of the basin we did not identify 2D resonance peaks.

The 2D resonance modes in Bolzano were investigated by Sgattoni and Castellaro (2020) also with synchronized recordings across the Adige valley to verify the in-phase motion at the 2D resonance frequencies identified in the absolute spectral components.

Directional analysis to infer 2D vibration main axes

To identify the main axes of motion and, therefore, infer the 2D vibration modes at all sites where these are observed, we then performed the directional analysis described earlier. The amplitude spectra of the rotated signals obtained at three example sites (located as in

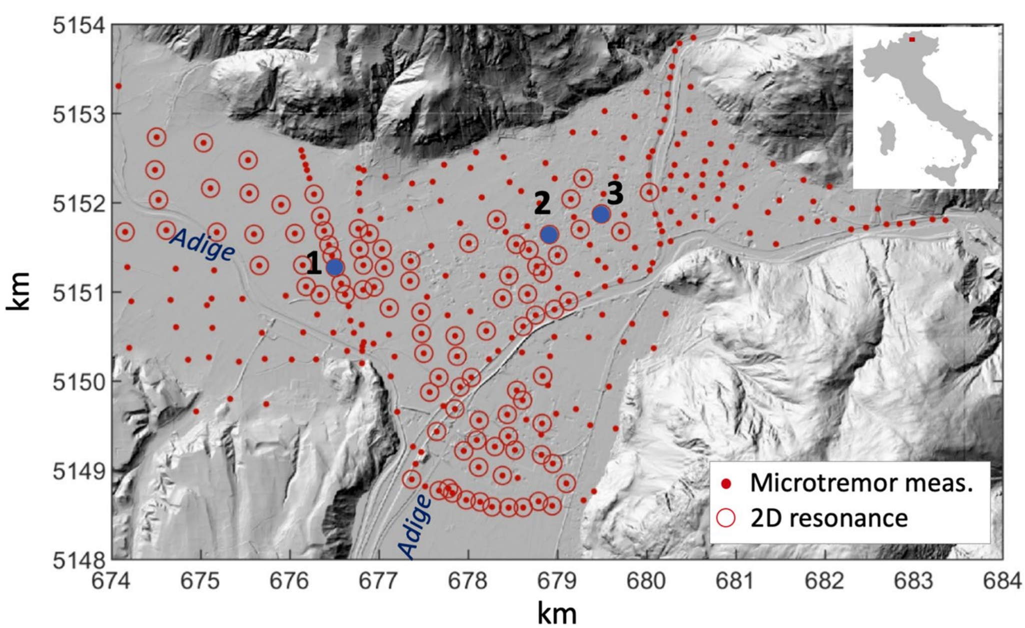


Fig. 6 Map of single-station microtremor measurements acquired in the Bolzano alluvial-sedimentary basin. and sites where 2D resonance modes were identified (Digital Terrain Model from Geoportale Alto Adige).

Fig. 6) are shown. The examples show different frequencies and amplitudes giving an idea of the variety of 2D resonance peaks observed within the basin. In all three cases, individual peaks along the x and y directions clearly appear to be best separated between each other at a specific rotation angle where they reach the maximum difference in frequency and amplitude. As anticipated in the method description, the frequency difference between the peaks Δf does not always peak at a single rotation angle θ (Fig. 7b), however, A_{LONG} does and its maximum value always coincides with a maximum value of Δf, as expected (Fig. 7c). L_0 corresponds to the peak at lower frequency and is characterized by higher amplitude with respect to T_0 (Fig. 7a). The directions of the local longitudinal axis of motion are evaluated at each site as shown in Fig. 7d and correspond to 80, 110 and 110 degrees from north at sites 1, 2 and 3, respectively. For comparison, we also calculated the azimuthal variation of H/V ratios with 10-degree angle steps for the same three measurement sites (Fig. 8). The directions corresponding to the maximum peak amplitude at the 2D resonance frequency (0.3–0.4 Hz) in this case are equal to 80, 120 and 130 degrees. These values are close to but do not always correspond to the longitudinal directions obtained with the method presented in this study. The reason for this discrepancy is that vibration modes investigation requires independent treatment of the components of motion.

Similar patterns were observed at all 101 sites and optimal rotation angles could be identified at all locations with the directional analysis proposed in this study. With this procedure, the estimation of the L_0 and T_0 frequencies is also optimized and does not depend on a priori choice of the instrument orientation (blue and green thick lines in Fig. 7a).

Spatial distribution and features of 2D resonance modes within the basin

Once the optimal rotation angle of the main vibration axes is identified at each site, the 2D longitudinal modes are then further analyzed in terms of directivity, frequency and amplitude patterns across the basin. The results are presented in Fig. 9, compared with the bedrock model of the basin by Sgattoni and Castellaro (2021).

Longitudinal directions

The longitudinal directions shown in Fig. 9a correlate well with the bedrock geometry shown in Fig. 9d. In particular, they align with the longitudinal axes of two main geological structures, i.e., two main valley channels joining in the center of basin. We will refer to these channels as Adige and Isarco valleys (Fig. 9d). The Adige valley is deeper (with maximum depth of about 700 m), intersects the western side of the basin with a NW–SE direction and turns to a roughly N–S direction in the southern part of the basin. The Isarco valley is shallower, has an E–W orientation in the central part of the basin and then turns into a NE–SW orientation and joins the Adige valley. Close to the junction of the Isarco and Adige valleys the pattern is more complicated, possibly due to 3D effects associated to the complex bedrock morphology; however, at the sites where 2D resonances were identified, the corresponding longitudinal directions are consistent with the direction of the valleys.

The buried geometries of the two valleys, therefore, can be inferred from the spatial distribution of the longitudinal directions at each site where 2D resonance is observed, as found by the presented procedure. This is an indication that 2D resonance develops across the buried channels that join in the center of the basin and that the directional analysis is of great help to identify these geological structures, even when they cannot be predicted from the surface geomorphology. This also implies that in the cases where the longitudinal and transverse directions are not known, the best instrument orientation cannot be decided in advance. A common orientation of all measurements and subsequent rotation is instead recommended.

2D longitudinal modes: frequencies and amplitudes

To analyze the frequency and amplitude distribution of the L_0 modes, we grouped the observed values into four ranges of frequency and amplitude (Fig. 9b, c). L_0 frequencies do not vary along cross-sections of each valley, as expected since any point in a valley slice must vibrate at the same frequency for each 2D mode. When moving along the longitudinal axes of the buried valleys, instead, L_0 frequencies correlate with the local aspect ratio of the valley: they are constant along the Adige valley, which is characterized by fairly stable geometry along its axis, while they increase from SW to NE along the axis of the Isarco valley, as the valley depth decreases. The varying L_0 frequency along the Isarco valley can be explained by the inverse relation of L_0 frequency with the maximum depth of the valley. This determines that, when spatial homogeneity of the sediment layer can be assumed, varying absolute values of 2D frequencies can be related to changing maximum depth of the valley along its axis. However, 2D frequencies are also dependent on the width of the valley, which makes the direct application of this rule less straightforward.

The spatial distribution of A_{LONG}/A_{VERT} correlates with bedrock geometry: maximum amplitude rates are observed along the deep Adige valley, while they are lower along the shallower Isarco valley. They also tend to correlate with bedrock geometry also along

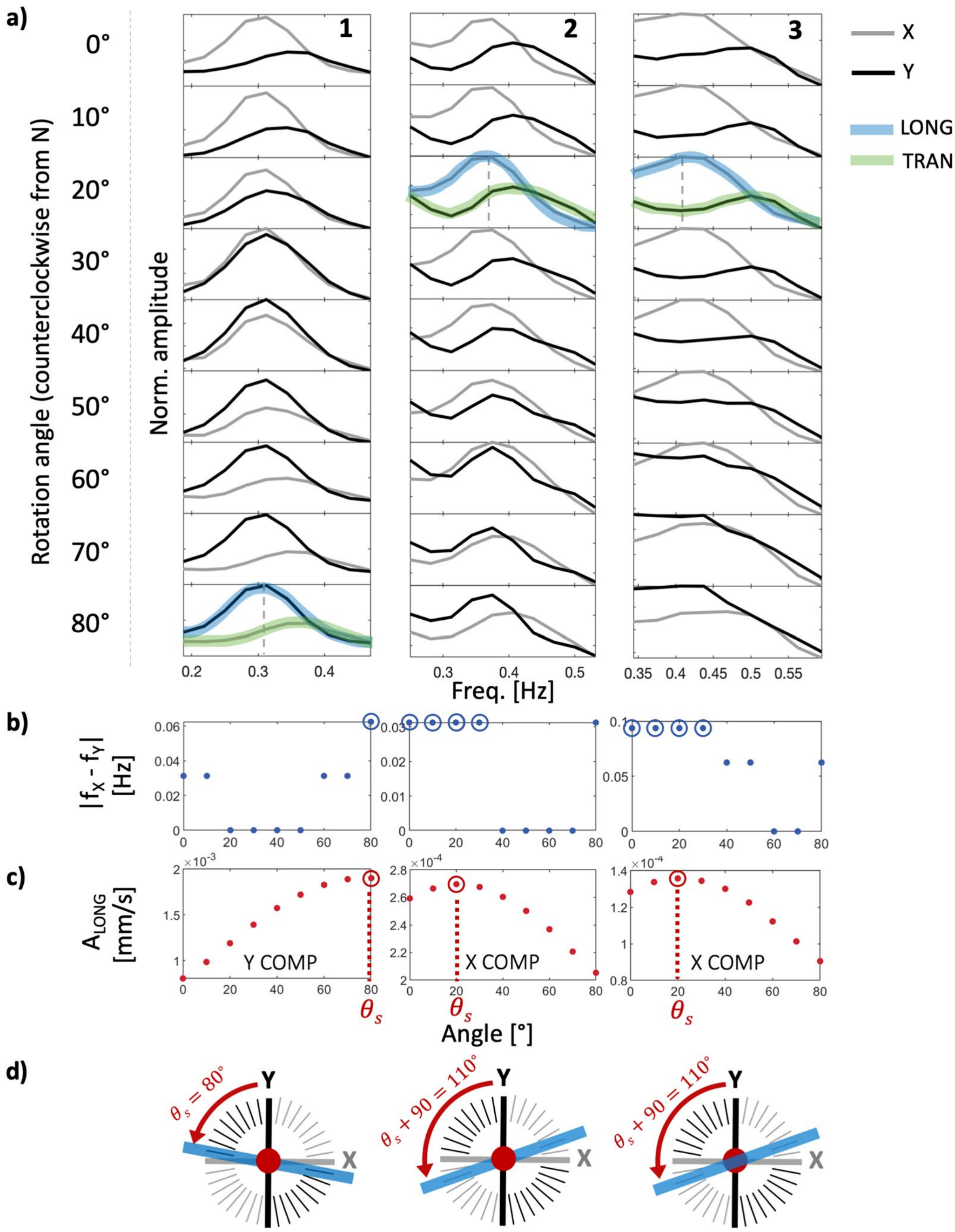


Fig. 7 Examples of directional analysis. The location of each example site is shown with a blue dot in Fig. 6. **a** Examples of rotated spectra between 0° and 80°. Grey and black lines are the instrumental *x* and *y* components, while blue and green lines identify the local longitudinal and transverse directions, at the selected rotation angle. **b** Frequency differences between resonance peaks observed along the instrumental *x* and *y* spectral components, for each rotation angle. The circles mark the angle(s) maximizing the frequency difference. **c** Spectral amplitude at the L_0 frequency (marked by vertical grey line in panel **a**) estimated along the x or y component as indicated on each plot. The circles mark the selected angle θ_S. **d** resulting longitudinal axis (blue line) for each example site at rotation angles corresponding to θ_S when the longitudinal direction is found on *y* instrumental component and to $\theta_S + 90°$ when it is found on the *x* component

cross-sections, with decreasing values towards the valley sides. This feature is observed mainly along the deeper Adige valley, where 2D resonances have higher amplitudes and are observed more extensively. The amplitude pattern along a valley cross-section depends on the modal shape. Maximum displacement amplitudes are expected close to the point of maximum valley depth.

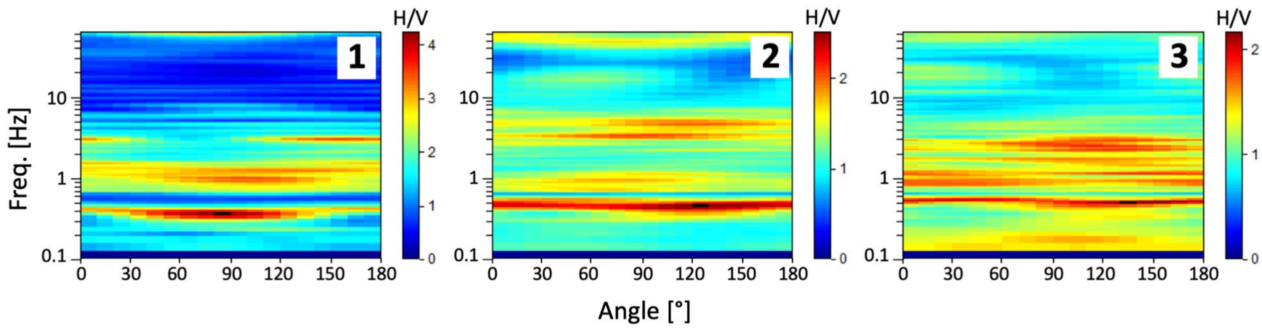


Fig. 8 Examples of directional *H/V* obtained with 10-degree angle steps at the same measurement sites shown in Fig. 7. The location of each example site is shown with a blue dot in Fig. 6. The maximum peak amplitude at about 0.3–0.4 Hz is observed for angles equal to 80, 120 and 130 degrees (counterclockwise from north)

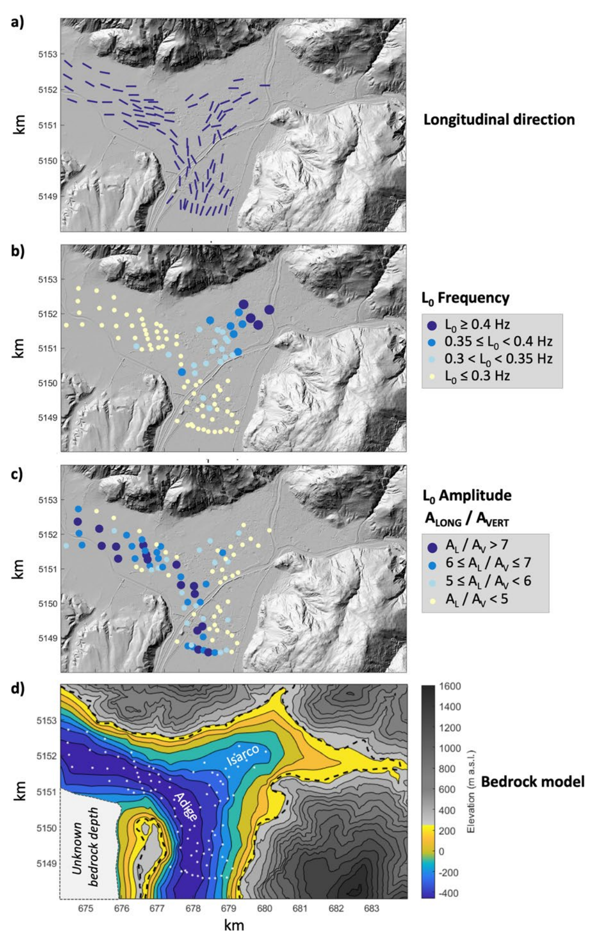


Fig. 9 Analysis of the L_0 mode at all investigated sites within the Bolzano basin. **a** orientation of local longitudinal directions. **b** L_0 frequencies, grouped into four intervals; **c** A_{LONG}/A_{VERT} amplitudes, grouped into four intervals. **d** Bedrock model (modified from Sgattoni and Castellaro 2021) and location of measured 2D resonances (white dots). Digital Terrain Model from Geoportale Alto Adige

These observations suggest that the morphology of the bedrock in the Bolzano basin can be 'decomposed' into 2D-like geometries, i.e., valleys, each with a longitudinal direction corresponding to its elongation axis. The observed resonances develop within cross-sections of these valleys, therefore, a change in orientation of the valley axis determines a change in orientation of the main axes of motion, that can be tracked with the method proposed in this study.

We also note that the observed patterns have an effect on the interpretation of H/V amplitudes (since H/V ratios derive from individual spectra), usually explained in terms of Rayleigh wave ellipticity and in relation with impedance contrast between sediments and bedrock. Also, previous observations of H/V peak amplitude decrease with sediment thickness increase (e.g., Albarello and Lunedei 2011) do not apply in our case, where maximum amplitudes are observed at sites with maximum bedrock depth. However, a full discussion on this matter is beyond the scope of this paper.

Uncertainties

It is not easy to quantify uncertainties; however, we discuss here a few possible issues. First of all, there is an experimental uncertainty in the instrument orientation on the ground that we quantify in about $\pm 10°$. This affects the estimation of the longitudinal directions, while it has no effect on the estimation of peak frequencies and amplitudes. Second, not all 2D peaks are clear. This correlates with amplitudes shown in Fig. 9c, with 2D peaks being clearest where higher amplitudes are observed. This is also seen in Fig. 6b. Estimated uncertainties on longitudinal and transverse fundamental frequencies in our case study are 0.01–0.02 Hz and 0.02–0.03 Hz, respectively. Third, spectral resolution affects the accuracy of the frequency estimation at the low frequencies investigated. Our analysis proved efficient with the acquisition parameters used, however, it would benefit from the use of longer acquisition duration, provided that a sufficient number of measurement points are used.

Discussion and conclusions

We presented a description of ground resonance patterns within a sedimentary basin. We started from a large set of single-station microtremor measurements where we identified 2D resonances that we distinguished from 1D resonances based on the inspection of the individual spectral components of motion. At the sites where 2D resonances were observed, we performed a directional analysis to infer the main axes of motion and correctly identify the longitudinal and transversal 2D resonance frequencies. When ground motion is recorded parallel to the longitudinal and transverse axes of a valley, the L_0 and T_0 resonance frequencies can be identified as distinct peaks on the instrumental horizontal spectral components. At oblique orientations, instead, their projections (different in frequency and amplitude) are recorded along the instrumental axes chosen for the measurements on the field. We, therefore, performed an azimuthal analysis of the spectral peaks identifying 2D resonances to detect the principal axes of motion, at each investigated site. The optimal orientation is the one that maximizes the amplitude spectrum at the resonance frequency and the frequency distance between L_0 and T_0. When these conditions are met, the rotated instrumental components correspond to the local longitudinal and transverse axes of the resonating structure, e.g., a buried alluvial valley, and the L_0 and T_0 frequencies and amplitudes can be estimated. We then focused further analysis on the L_0 modes by investigating their directionality, frequency and amplitude features across the basin.

The proposed method for directional analysis of 2D resonances relies on a simple procedure that is applicable, also in the daily practice, to single-station microtremor measurements. Compared to other classical methods based on particle motion polarization analysis, it does not need long-duration measurements, nor synchronized array measurements; it does not imply a priori decisions on filtering and it is less influenced by noise sources that could alter the interpretation of particle polarization when this is not averaged over long times. The method is similar to the azimuthal analysis of H/V ratios, but is performed on the individual horizontal spectral components rather than combining them: this is necessary as we seek for the direction at which the separation between the two horizontal resonance peaks is maximum. In addition, 2D transverse modes have a vertical component, which in the H/V, N/V or E/V ratios would be mixed up with the horizontal components.

The application of our analysis to a large number of single-station microtremor measurements in the Bolzano sedimentary basin suggested that apparently complex resonance patterns may be unraveled by referring to the description of 2D resonance of a valley slice. We observed that longitudinal directions, L_0 amplitudes and L_0 frequencies carry useful information on the buried bedrock geometry and suggest that observed 2D resonances within the basin may be viewed as superimposition of 2D resonance modes developing along 2D-like geometries, i.e., valleys, each with a longitudinal direction corresponding to its elongation axis. L_0 frequencies are constant within cross-sections of the valleys while they vary along the valley axes when the geometry of the valley cross-section changes, i.e., in our case, when bedrock depth changes (although a similar effect would be produced by a change in valley width). L_0 amplitudes vary both along the longitudinal and transverse valley axes, somehow correlating with bedrock depth. The relation between amplitudes and bedrock shape is, however, more complex and beyond the goals of the present paper. All this information may help interpreting 2D resonances, even in the complex case of a sedimentary basin, the buried geometry of which cannot be easily predicted from the surface morphology. This should be complemented with identification of 1D-type frequencies that are directly correlated with bedrock depth and are observed in the valleys with lower aspect ratio.

The patterns of 2D resonances observed in the Bolzano basin may differ from other sites with different bedrock geometries. The Bolzano plain lies at the junction between Alpine valleys creating an alluvial-sedimentary basin. The bedrock geometry is composed of excavated channels, each acting with a 2D dynamic behavior such as that of an Alpine valley.

The presence and orientation of the buried channels is not apparent from the surface morphology but can be inferred with the directional analysis proposed in this study. We believe that similar patterns may be observed in other alluvial-sedimentary basins. More complicated 3D resonance patterns may instead arise in sedimentary basins where the bedrock geometry cannot be decomposed into 2D geometries (e.g., bowl-shaped basins). In this case, 3D resonances could also result in directional motion and the presented procedure could be applied to investigate them; however, their spatial interpretation would be different than in the case of 2D geometries.

The proposed procedure can be useful to investigate buried sedimentary bodies that do not have a morphological evidence (e.g., paleovalleys; Amorosi et al. 2016) and we believe it can be applied also in different geologic contexts, e.g., for the investigation of topographic effects or to landslides. For example, an unstable mass on a slope could be viewed as an equivalent to a sediment fill of a valley, with its own directional vibration modes, as noted also by Burjánek et al. (2010).

Our study relied on the analysis of a large number of short-duration measurements covering the whole basin, which is necessary for a comprehensive description of the phenomenon and to analyze the overall patterns within the basin. We tested our acquisition and processing strategy for statistical significance and stability over time. The analysis would anyway benefit from the use of longer-duration acquisitions, which allows for better spectral resolution, especially at the low frequencies investigated. The same procedure can also be applied to higher frequencies, i.e., to smaller scale valleys/basins.

Our study has also practical consequences for the use of H/V ratios to study ground resonances. In addition to the importance of detecting 2D resonance on individual spectral components as noted also by previous studies, we note that directional analyses should be performed on individual components of motion and not on the H/V functions, as often done in practical applications. Also, the correlation of amplitudes with bedrock depth (as a function of 2D modal shapes), suggests that care should be taken when modelling H/V functions in terms of Rayleigh wave ellipticity as a function of impedance contrast.

The procedure proposed in this paper, in addition to the features described by Sgattoni and Castellaro (2020) to distinguish 1D/2D resonances, can be applied routinely to single-station measurements besides the H/V analysis, which is a popular technique to investigate seismic site effects and for stratigraphic reconstructions, especially in urbanized areas.

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Author contributions

GS designed the work, planned and conducted the data acquisition, analysis and interpretation, wrote the manuscript and drew the relevant figures. GL contributed to the data acquisition and analysis. SC supervised the project. SC wrote the processing codes and GS wrote the analysis codes. All authors contributed to the discussion of results. All authors read, revised and approved the final manuscript.

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Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests

The authors declare that they have no competing interests.

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References

Albarello D, Lunedei E (2011) Structure of an ambient vibration wavefield in the frequency range of engineering interest ([0.5, 20] Hz): insights from numerical modelling. Near Surf Geophys 9:543–559. https://doi.org/10.3997/1873-0604.2011017

Amorosi A, Bracone V, Campo B, D'Amico C, Rossi V, Rosskopf CM (2016) A late Quaternary multiple paleovalley system from the Adriatic coastal plain (Biferno River, Southern Italy). Geomorphology 254:146–159

Bard P-Y, Bouchon M (1980a) The seismic response of sediment-filled valleys. Part I. The case of incident SH waves. Bull Seism Soc Am 70:1263–1286

Bard P-Y, Bouchon M (1980b) The seismic response of sediment-filled valleys. Part 2. The case of incident P and SV waves. Bull Seism Soc Am 70(5):1921–1941

Bard P-Y, Bouchon M (1985) The two-dimensional resonance of sediment-filled valleys. Bull Seism Soc Am 75:519–541

Burjánek J, Gassner-Stamm G, Poggi V, Moore JR, Fäh D (2010) Ambient vibration analysis of an unstable mountain slope. Geophys J Int 180:820–828

Burjánek J, Edwards B, Fäh D (2014) Empirical evidence of local seismic effects at sites with pronounced topography: a systematic approach. Geophys J Int 197(1):608–619. https://doi.org/10.1093/gji/ggu014

Di Giulio G, Cara F, Rovelli A, Lombardo G, Rigano R (2009) Evidences for strong directional resonances in intensely deformed zones of the Pernicana fault, Mount Etna, Italy. J Geophys Res 114:B10308. https://doi.org/10.1029/2009JB006393

Del Gaudio V (2017) Instantaneous polarization analysis of ambient noise recordings in site response investigations. Geophys J Int 210(1):443–464. https://doi.org/10.1093/gji/ggx175

Ermert L, Poggi V, Burjánek J, Fäh D (2014) Fundamental and higher two-dimensional resonance modes of an Alpine valley. Geophys J Int 198(2):795–811. https://doi.org/10.1093/gji/ggu072

Frischknecht C, Wagner JJ (2004) Seismic soil effect in an embanked deep alpine valley: a numerical investigation of two-dimensional resonance. Bull Seism Soc Am 94(1):171–186

Guillier B, Cornou C, Krister J, Moczo P, Bonnefoy-Claudet S, Bard PY, Fäh D (2006) Simulation of seismic ambient vibrations: does the H/V provide quantitative information in 2D-3D structures? In Third International Symposium on the Effects of Surface Geology on Seismic Motion, Grenoble, France, 2006 September 1–August 28, LCPC, Bard, P.Y., Chaljub, E., Cornou, C., Cotton, F., Gueguen, P., 185 pp.

Jurkevics A (1988) Polarization analysis of three component array data. Bull Seism Soc Am 78:1725–1743

Keim L, Mair V, Morelli C (2013) Inquadramento geologico regionale, In Carta Geologica dell'Alto Adige, guida ai percorsi geologici, Foglio 026 Appiano. LAC Firenze, https://maps.civis.bz.it/. Accessed 25 Mar 2022.

King JL, Tucker BE (1984) Observed variations of earthquake motion across a sediment-filled valley. Bull Seism Soc Am 74(1):137–151

Le Roux O, Cornou C, Jongmans D, Schwartz S (2012) 1-D and 2-D resonances in an Alpine valley identified from ambient noise measurements and 3-D modelling. Geophys J Int 191(2):579–590

Matsushima S, Kosaka H, Kawase H (2017) Directionally dependent horizontal-to-vertical spectral ratios of microtremors at Onahama, Fukushima, Japan. Earth Planets Space 69:96. https://doi.org/10.1186/s40623-017-0680-9

Moczo P, Labák P, Kristek J, Hron F (1996) Amplification and differential motion due to an antiplane 2D resonance in the sediment valleys embedded in a layer over the half-space. Bull Seism Soc Am 86(5):1434–1446
Molnar S, Sirohey A, Assaf J, Bard P-Y, Castellaro S, Cornou S, Cox B, Guillier B, Hassani B, Kawase H, Matsushima S, Sánchez-Sesma FJ, Yong A (2022) A review of the microtremor horizontal-to-vertical spectral ratio (MHVSR) method. J Seismol. https://doi.org/10.1007/s10950-021-10062-9
Nakamura Y (1989) A method for dynamic characteristics estimates of subsurface using microtremor on the ground surface. Quart Rep Railway Tech Res Inst 30:25–33
Panzera F, Pischiutta M, Lombardo G, Monaco C, Rovelli A (2014) Wavefield polarization in Fault Zones of the Western Flank of Mt. Etna: observations and fracture orientation modelling. Pure Appl Geophys 171:3083–3097. https://doi.org/10.1007/s00024-014-0831-x
Rial JA (1989) Seismic wave resonance in 3-D sedimentary basins. Geophys J Lnt 99:81–90
Roten D, Fäh D, Cornou C, Giardini D (2006) Two-dimensional resonances in Alpine valleys identified from ambient vibration wavefields. Geophys J Int 165(3):889–905
SESAME Project (2004) Guidelines for the implementation of the H/V spectral ratio technique on ambient vibrations: measurements, processing and interpretation. SESAME European Research Project WP12, deliverable no. D23.12.
Sgattoni G, Castellaro S (2020) Detecting 1-D and 2-D ground resonances with a single-station approach. Geophys J Int 223(1):471–487. https://doi.org/10.1093/gji/ggaa325
Sgattoni G, Castellaro S (2021) Combining single-station microtremor and gravity surveys for deep stratigraphic mapping. Geophysics 86(5):77–88. https://doi.org/10.1190/geo2020-0757.1
Steimen S, Fäh D, Kind F, Schmid C, Giardini D (2003) Identifying 2D resonance in microtremor wave fields. Bull Seism Soc Am 93(2):583–599
Suzuki Y, Iiyama K, Morikawa H, Sakai K, Araki G (2021) New method to estimate bedrock shape of small-scale basin using modal properties of sediment. Soil Dyn Earthq Eng 149:106882. https://doi.org/10.1016/j.soildyn.2021.106882
Vidale JE (1986) Complex polarisation analysis of particle motion. Bull Seism Soc Am 76:1393–1405

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