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ORIGINAL ARTICLE

Integrated geophysical-geological model for seismic local site response: the Caldes alpine slope case (Southern Alps, NE Italy)

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Abstract We present the seismic local response analysis of an alpine slope based on an integrated geophysical and geological model. The studied site is located in Caldes, in the lower Val di Sole valley in the Trentino region, Southern Italian Alps. Caldes represents the typical alpine valley formed by glacial and fluvio-glacial processes characterized by complex geomorphological, lithological and tectonic settings. A detailed reconstruction of the valley slope geology (subsoil geometry and stratigraphy) was obtained using electrical tomography resistivity soundings, controlled source multi-channel analysis of surface waves, microtremor single station measurements, borehole investigations, and geotechnical analyses on undisturbed samples. The geological model was shaken with real accelerometric series to obtain 1D (linear equivalent approach) and 2D (finite element approach) local seismic responses. The results, considering the uncertainties of the geophysical measurements, show different seismic responses between 1D and 2D approaches due to relevant geometrical amplifications, with clearer variations in the 2D approach. The comparison of the results with the building code design spectra shows the limits of the simplified approaches, suggesting that detailed characterizations are necessary, especially for such populous alpine environments.

Keywords Slope seismic response · Geophysical prospecting · Shear-wave velocity measurements · Seismic hazard

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Introduction

Subsoil geometry has important consequences for local seismic response (Jongmans et al. 1998; Bard and Riepl-Thomas 2000; Boaga et al. 2012) and, consequently, on earthquake engineering design, especially in complex geological settings (Bard and Bouchon 1985; Bard 1994; Makra et al. 2002). Seismic motion can be modified and amplified by morphological effects (Assimaki et al. 2005), buried geological structures (Naganoh et al. 1993), and lithological contrasts (Seed and Idriss 1969). Advanced seismic response analyses must consider all of these aspects for virtual earthquake ground motion prediction techniques (Denolle et al. 2014).

Theoretical ground response analysis, based on the synthetic shaking of a modeled structure, is the common approach for evaluating the contribution of the subsoil properties to seismic motion (Aki and Larner 1970). The approach is founded on the assumption that surface motion amplification is a consequence of elastic wave energy conservation. Modifications of seismic motion mainly derive from the shear modulus of materials and their ability to dissipate energy. The transverse component of motion is predominant, because shear-wave velocities (V_s) and densities are usually smaller near the surface than at greater depth. For this reason, a correct characterization of V_s is crucial, especially at shallow depths, considering that seismic waves may travel through kilometers of rigid crust and <100 m of soft soil (Bard and Bouchon 1985).

Transfer functions are generally used in earthquake engineering to describe the relationship between input motion at the soil model base and the resulting shaking of the surface ground. This approach is based on the principle of superposition, which iteratively analyses a nonlinear system by approximating equivalent linear soils. Synthetic ground motions generate transfer functions for layered soils characterized by specific values of shear modulus, damping, and density (Seed and Idriss 1969). The most widely used codes are based on linear equivalent analysis by continuous layer discretization in the frequency domain as well as SHAKE (1D models; Schnabel et al. 1972; Idriss and Sun 1992), QUAD-4 (2D models; Idriss et al. 1973), and Flac3D codes (3D models; Itasca Consulting Group Inc 1997). Seismic ground response can be estimated in both the linear (or equivalent linear, e.g., weak motion), and fully nonlinear ranges (e.g., strong motion). Nevertheless, the accuracy of seismic response modeling is strongly constrained by how realistic the description of the subsoil is and the specific characterization of material dynamic behaviors (Gelagoti et al. 2012). In this sense, mountain slopes are considered difficult cases, being characterized by multi-dimensional geometries. Urbanized alpine environments generally show variable topography, often coupled with unknown buried geometries and different lithologies. Even if the selection of realistic earthquake input can now be solved by replete digital databases, a realistic geological model remains the weakest point of every seismic scenario. Complete knowledge of subsoil geometry and material properties, including shear-wave velocity, density, shear modulus, and damping, is particularly rare for mountain slope complex environments (Stokoe et al. 1999). Mountain slope characterization needs in situ detailed geophysical measurements integrated with geological surveys and laboratory geotechnical analyses.

Here we present the seismic response analysis of the alpine site of Caldes (Trentino, Southern Alps, Italy), a small municipality with about 1000 citizens (2014 census) of the lower 'Val di Sole' valley. Due to the absence of moderate to strong historical and instrumental seismicity (Boschi et al. 1997; Viganò et al. 2008), Caldes represents a typical and widely diffused weak-motion alpine case study, representative of the alpine environment. In fact, the expected value of Peak Ground Acceleration (PGA) from the Italian seismic hazard map (http://esse1-gis.mi.ingv.it/) is 0.050 g, for a 475 years return period and a rock reference site. We obtained a realistic subsoil model of a single slope of the valley based on the results of an integrated geophysical and geological investigation. We applied electrical tomography, seismic surveys, microtremor measurements, borehole drillings, and geotechnical laboratory analysis. The model obtained was then shaken with different 1-D and 2-D approaches and several real seismic inputs. The results were then compared with Norm design spectra. The analyses suggest that simplified 1-D norm approaches are not applicable for mountain slopes, even for the relative moderate seismicity of this sector of the Southern Alps.

Geological setting

Caldes is a small municipality located on the left side of the lower Val di Sole (NW Trentino), a narrow valley with an asymmetric setting. This valley is broadly delimited by basement rocks on the north-western side (Tonale nappe) and by carbonate covers of mainly Middle Triassic age on the south-eastern side (Brenta Dolomites) (Fig. 1a).

The study area is located at the junction of the Tonale (ENE–WSW oriented) and the Giudicarie fault systems (NNE–SSW oriented), structurally bordered to the east by the Trento–Cles faults (N–S oriented, Dal Piaz et al. 2007). Near Caldes (at Samoclevo, Fig. 1a), the tectonic contact (Giudicarie fault system) between metamorphic and sedimentary rocks cross cuts the valley. Here, clay-rich limestones and torbidites (Val d'Agola Fm.) overthrust marly limestones (Calcari Grigi Group).

Val di Sole and lateral valleys (e.g., Val di Peio and Val di Rabbi) were covered by glaciers during the last glacial periods (Penck and Brückner 1909), and most of glacial Quaternary deposits are of Late Pleistocene and Holocene ages (Garda synthem; Dal Piaz et al. 2007). The lower Val di Sole shows two typical orders of terraces, the first composed of glacial, debris flow and alluvial fan deposits (Pleistocene age) located at higher altitude (cf., Samoclevo in Fig. 1), the second composed of dominant alluvial and minor glacial deposits (Holocene age) placed at lower altitude (cf., Caldes in Fig. 1). Near Caldes, alluvial deposits of the Noce River have a thickness of about 40–60 m (minimum thickness estimated from the lateral scarps of the river) and include heterogeneous pebble gravels and coarse sands, the latter with well-developed layering. The studied slope is characterized by gentle slope in the upper part and a steeper slope toward the river (Fig. 1b). Gravels and coarse sands are generally interbedded with silty and sandy lenses of variable thickness. Local landslide deposits, typically bordered by clear landslide scarps, are due to rockfalls or debris-flows.

Active deformation in NW Trentino is testified by sparse low-grade seismicity (moment magnitude <5.0), locally mainly concentrated within the Tonale nappe (hangingwall of the North Giudicarie fault). The most important seismic

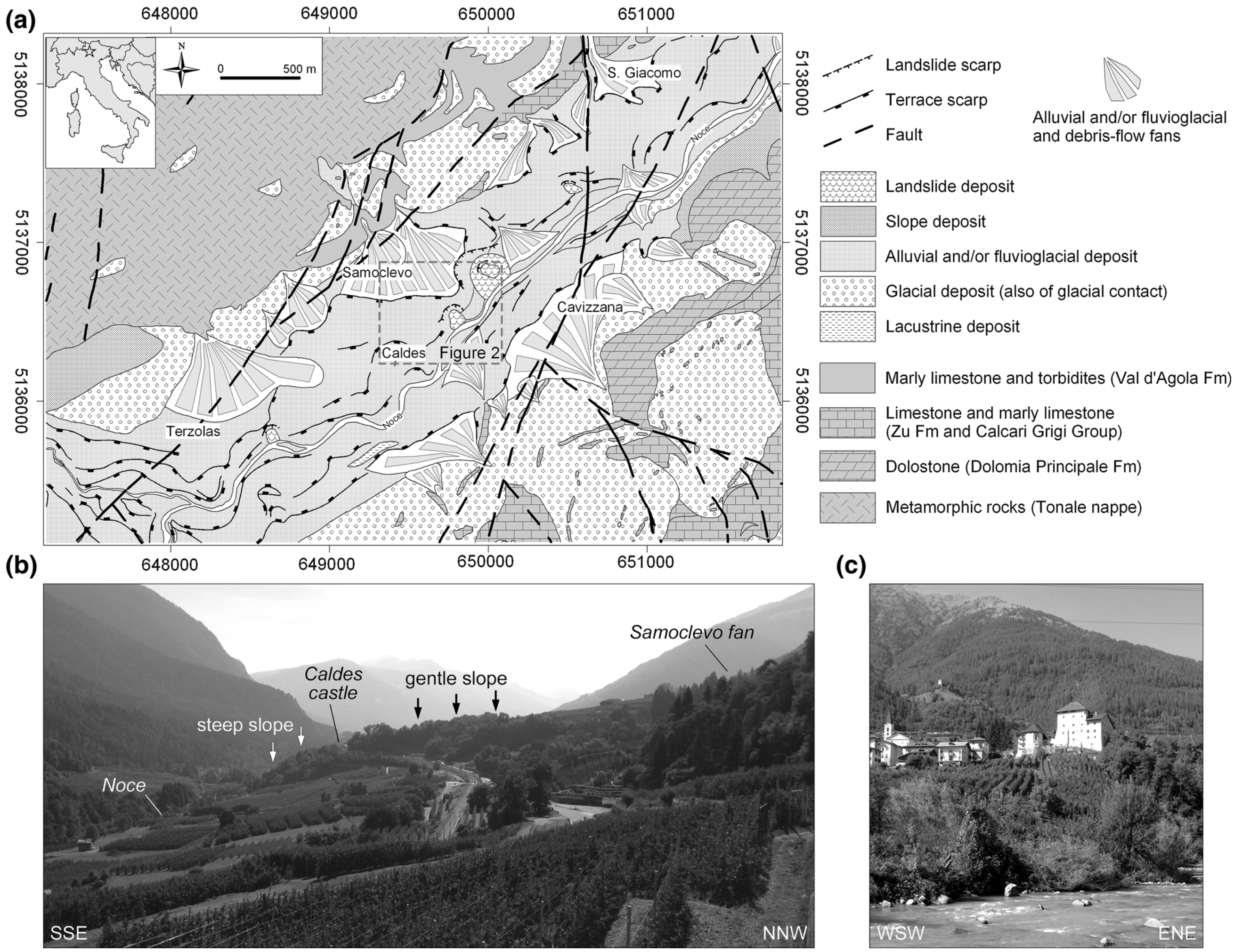

Fig. 1 **a** Simplified geological map of the lower Val di Sole (NW Trentino). The central box delimits the study area (Fig. 2). **b** Panoramic view of the Val di Sole northern slope from the upper Samoclevo fan to the Noce river. The Caldes and Samoclevo villages are located just on the other side of the woody ridge. **c** The lower portion of the slope, between the castle (in the middle of the photograph) and the Noce river. The central box delimits the study area (Fig. 2)

events occurred about fifty kilometers to the northwest (Gran Zebrù fault) and to the northeast (Merano earthquake, July 17th 2001, duration magnitude 4.8, see Viganò et al. 2008, 2013), even if the study area can be also affected by earthquakes occurring more to the south (active Giudicarie southern belt).

Geophysical and geotechnical characterization

The Caldes integrated model derives from the integration of different types of surveys: (1) electrical resistivity tomography to investigate subsoil structure; (2) controlled source seismic surveys via multi-channel analysis of surface waves and frequency-time analysis to measure shear-wave velocities; (3) microtremor single station horizontal-to-vertical spectral ratio analysis to detect main impedance contrasts; and (4) laboratory analyses on undisturbed samples to define dynamic material properties. The surveys involved both the northern mountain slope near the 'Samoclevo' village and the southern one, close to the 'Caldes' village, around a historical medieval castle (see Figs. 1c, 2).

Electrical resistivity tomography

We collected 2 electrical resistivity tomography (ERT) arrays with different electrode spacing and acquisition schemes (Syscal-pro georesistivimeter and stainless steel electrodes). ERT1, located in the Caldes slope, used 48 channel acquisition with electrode spacing of 5 m for a total array length of 235 m. We adopted both a Wenner–Schlumberger acquisition scheme (Fig. 3a) and a dipole–dipole skip 0 acquisition scheme, completed with

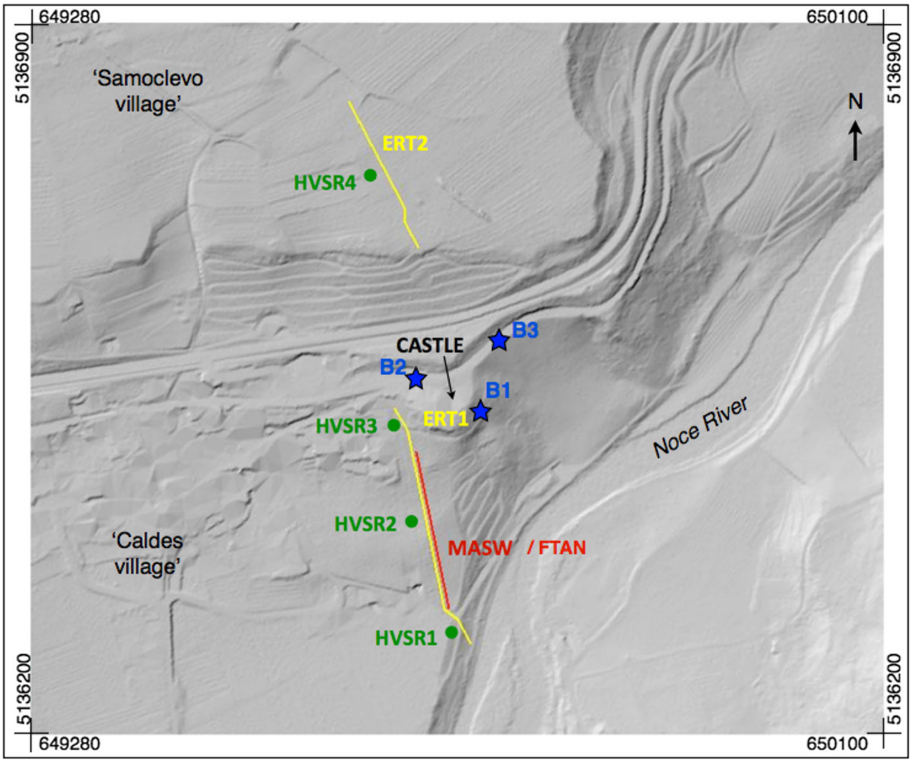

Fig. 2 Distribution of in situ analyses (DTM LIDAR map with 1 m resolution): electrical resistivity tomography arrays (ERT1 and ERT2 in *yellow*), controlled source seismic arrays (MASW and FTAN, in *red*) and single station microtremor measurements (HVSR1–4, in *green*). B1, B2, and B3 are boreholes where samples for geotechnical analyses were collected. 'Castle' indicates the Caldes medieval castle

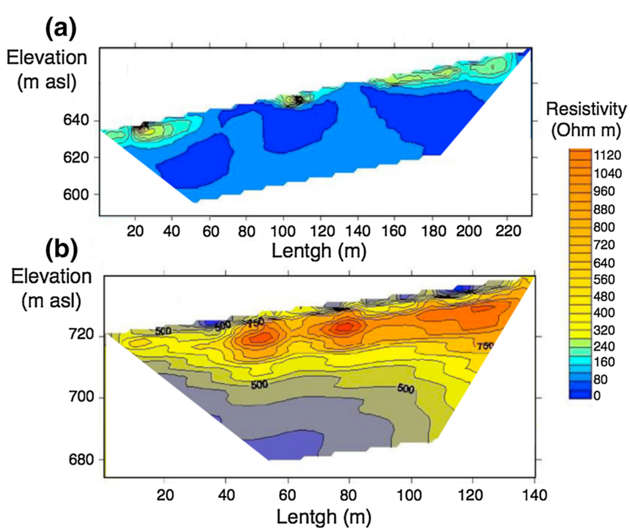

Fig. 3 **a** ERT1 inverted resistivity profile near Caldes, in the southern portion of the slope. Since Wenner–Schlumberger and dipole–dipole acquisitions present similar results, we show the former. **b** ERT2 inverted resistivity profile near Samoclevo, in the northern part of the slope. See the array locations in Fig. 2

reciprocal data to estimate the error level (e.g., Monego et al. 2010). For data inversion, we used an Occam approach implemented in the ProfileR software package (Binley 2011). We adopted an acceptable error threshold for direct and reciprocal potential measurements between quadripoles that could not exceed 5 % of the value. For ERT2, located near the 'Samoclevo' village, we used a 48 channel array with 2 m spacing for a total array length of 94 m, with a dipole–dipole skip 0 acquisition scheme (Fig. 3b). In addition, in this case, we recorded direct and reciprocal measurements with a fixed error threshold of 5 % between the same quadripoles.

Controlled source seismic analysis of surface waves

To measure in situ shear-wave velocities, we performed a multi-channel analysis of surface waves (MASW, Park et al. 1999) and a frequency-time analysis (FTAN, Levshin et al. 1972; Boaga 2013). The MASW and FTAN arrays have the same position, located in the southern part of the slope (Fig. 2). For the MASW acquisition, we adopted a 24 bit digital seismograph and 48 vertical geophones with 4.5 Hz eigenfrequency. A seismic cal. 8 gun with a physical trigger was used as the source. Geophone spacing was 3 m for a total array length of 144 m. Source offset was 6 m, sampling was 0.25 ms, and the total length of recording was 2 s for every shot. For the FTAN array, we adopted the cal. 8 seismic gun as the source and, a 1 Hz

3-component geophone placed at 96 m from the source as the receiver. The nonlinear inverse problem of the dispersion curve was solved with the SWAMI code (Lai and Rix 1998) for the MASW data, while FTAN data were inverted with the nonlinear Hedgehog method (Valyus et al. 1968). Both of the techniques produced profiles of the shear-wave velocities in depth (Seismic records, spectra, and V_s profiles are shown in Fig. 4).

Single station microtremor survey

The single station horizontal-to-vertical spectral ratio method (HVSR, Nogoshi and Igarashi 1970) is based on the principle that average spectral ratios of ambient vibrations in the horizontal and vertical directions can supply information about the seismic resonance of the subsoil (Field and Jacob 1993; Ibs-von Seht and Wohlenberg 1999). Most researchers agree that the maximum of the *H*/*V* ratios in the frequency domain provides a good estimate of the fundamental resonance frequency (F_0) of a site, at least in the presence of identifiable impedance contrast in the subsoil (Lachetl and Bard 1994; Boaga et al. 2011). This parameter is directly related to the thickness of the soft soil cover and to the mechanical properties of soil and rock layers. HVSR is intensively used in seismic microzonation and geological surveys (SESAME 2004; Galgaro et al. 2013). Several studies have already applied these noise measurements for mapping the thickness of soft sediments (Nakamura 1989; García-Jerez et al. 2006) even if 2-D valley geometry poses critical interpretation of the results (Le Roux et al. 2012). The seismometer used is a 24-bit digital instrument, equipped with 3 orthogonal velocimeters with noise threshold <0.5 μV r.m.s. at 128 Hz sampling and a frequency response rate between 0.1 and 256 Hz. The instrument is installed with a spirit level with a horizontal high precision of sensitivity of 5′ arc (0.083°). Each acquisition lasted 32 min with 128 Hz sampling rate. The Horizontal-to-Vertical spectral ratio (HVSR) was obtained by computing the quadratic mean of the two horizontal components with a smoothing of 10 % and with windows (according to Konno and Ohmachi 1998) of 20 s. Figure 5 shows the HVSR results for the four measurement points (locations are shown in Fig. 2).

Geotechnical analyses

Geotechnical analyses were performed on samples from three boreholes (B1, B2, and B3 in Fig. 2). Borehole depths varied from 15 m (B1) to 25 m (B2–B3) without reaching the bedrock. In the geotechnical laboratory, seven undisturbed samples were classified (index properties; average unit weight 20 kN m^{-3}) and tested for mechanical resistance and deformability (oedometer, triaxial, and hydraulic conductivity tests). Moreover, other 23 samples were

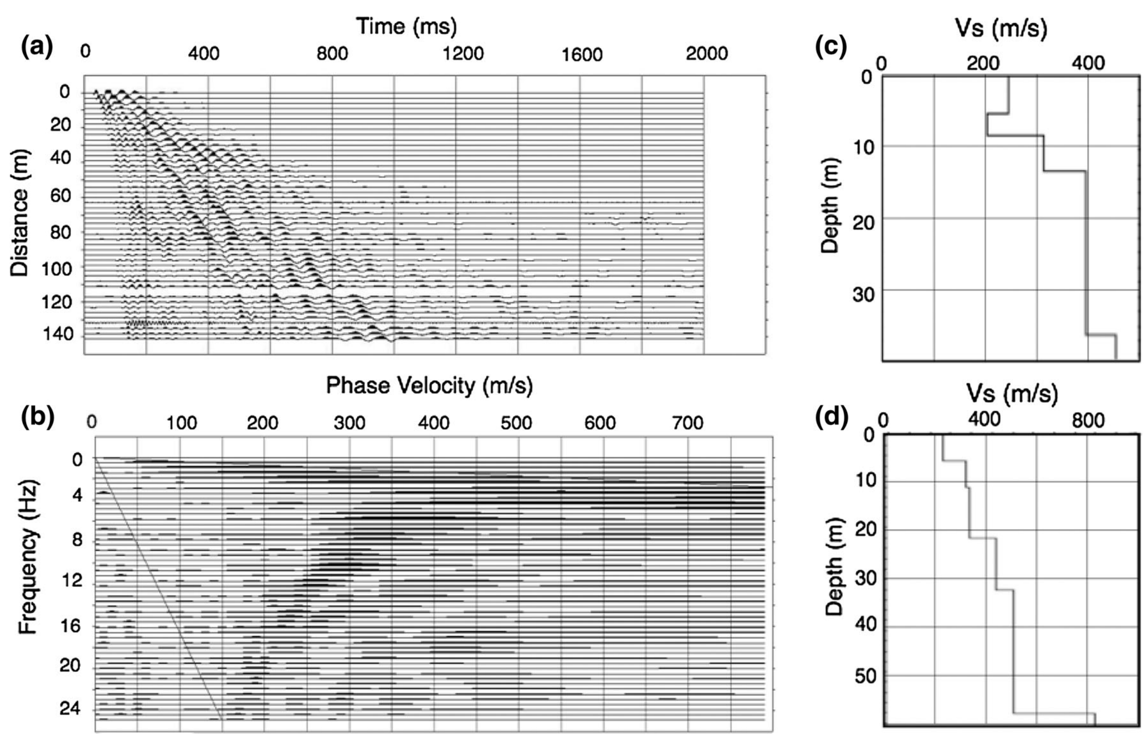

Fig. 4 Surface wave analysis results: **a** example of seismic records for Caldes; **b** example of Phase velocity-Frequency spectrum of the seismic record in “a”; **c** shear-wave profile after inversion from MASW data; **d** shear-wave profile after inversion from FTAN data

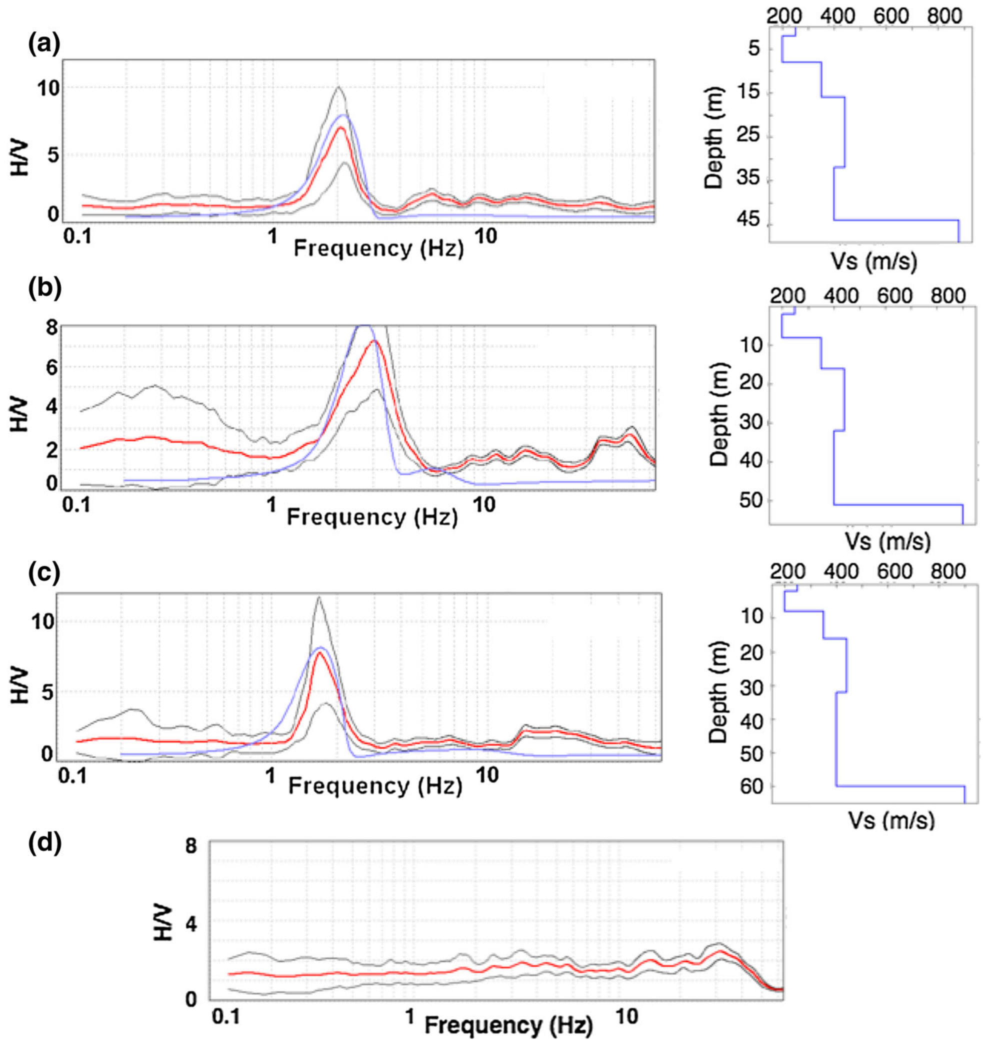

Fig. 5 HVSR results (*a–d* are HVSR1–HVSR4, cf., Fig. 2). In *red*, the experimental HVSR curves; in blue, the synthetic HVSR curves resulting from the V_s/depth considered profiles (*right panels*). *Note* that the Samoclevo site shows a flat spectrum (HVSR4)

collected from cores at regular length intervals and then classified (index properties).

Classifications identify three main granulometric groups (clayey silts, sands, and sandy gravels) and broadly confirm geological observations (Dal Piaz et al. 2007; Fig. 6a). *Atterberg* limits on clayey silts classify (1) medium-plasticity clays (14 samples), (2) low-plasticity clays (4 samples), and (3) silts (2 samples).

Cyclic Torsional Shear (CTS) and Resonant Column (RC) tests (Stokoe et al. 1980 fixed-free equipment) were performed on undisturbed clayey silts and reconstituted sands. Sands were reconstituted including all grain size distributions and paying attention to the maximum grain–specimen diameter ratio. Tests on sandy gravels were not possible due to their large grain size. For each experiment, CTS was performed up to the elastic–plastic threshold and preceded RC on the same specimen.

Figure 6b shows the normalized shear modulus and damping curves obtained from RC for selected clayey silts (2 samples) and sands (2 samples). Experimental curves were selected considering consolidation pressures possibly closer to the expected in situ effective stresses, to better support numerical models.

Experimental curves largely agree with typical literature data (a–d in Fig. 6b), both for normalized shear modulus and damping. In particular, very similar values of normalized shear modulus were obtained for clayey silts (up to about 0.01 %, cf., b in Fig. 6b left diagram). The experimental damping values for clayey silts lie generally between Vucetic and Dobry (1991) curves obtained for different plasticity indexes (15–50; a–b in Fig. 6b right diagram). Sand experimental data are between sand (lower limit) and gravels literature curves (Seed and Idriss 1970; Rollins et al. 1998), especially for the normalized shear modulus. A comparison of initial shear modulus values (G_0) between RC laboratory data (interpolating G_0 measurements at different consolidation pressures during a multistage consolidation test) and in situ estimates (from

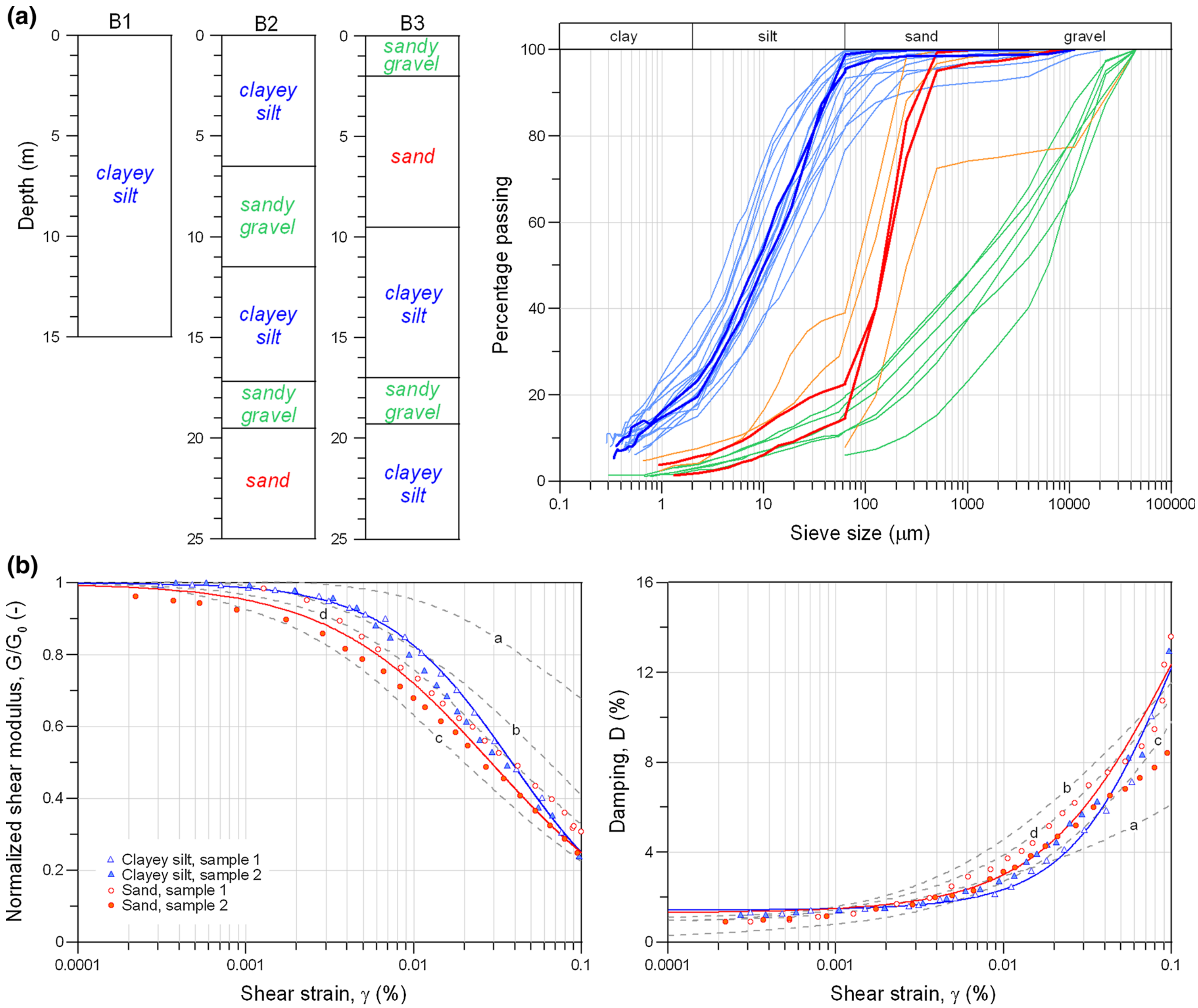

Fig. 6 **a** Simplified stratigraphy of the three studied boreholes (B1–3) and granulometric curves (23 analyzed samples) with colors to identify different lithologies. The *bold curves* are referred to selected samples (#2 clayey silts and #2 sands) examined by dynamic experiments (cf., Fig. 6b). **b** Normalized shear modulus and damping experimental curves (clayey silt, *blue*; sand, *red*). For each lithology, both experimental values and interpolated curves (Yokota et al. 1981 interpolation method) are shown. Consolidation pressures were 200 kPa (clayey silts) and 300 kPa (reconstituted sands). *Dotted gray lines* are reference literature curves: *a* clayey silts, plasticity index = 50 (Vucetic and Dobry 1991); *b* clayey silts, plasticity index = 15 (Vucetic and Dobry 1991); *c* sands, lower range curve (Seed and Idriss 1970); *d* gravels (Rollins et al. 1998)

MASW technique) was performed. For the best-quality undisturbed clayey silts, very similar values were obtained within the range of effective stress corresponding to the stratigraphic model (71–84 MPa laboratory G_0, 80–81 MPa in situ G_0).

Model description

ERT soundings allow reconstructing the thickness of Quaternary sediments and the bedrock geometry. The ERT1 cross section, located in the Caldes slope, does not present relevant heterogeneities of electrical properties and does not show resistivity values compatible with the bedrock until a depth of 40–50 m (Fig. 3a). ERT1 results thus suggest a thick soil cover characterized by low resistivity (<100 Ω m), to be interpreted as partially saturated sediments. This evidence is confirmed by the slope boreholes that show drilled layers of sand, clayey silt, and gravel without intercepting the geologic bedrock (Fig. 6). On the contrary, the ERT2 cross section at the Samoclevo site shows high resistivity values (>950 Ohm m) just a few meters below the surface (<3–4 m depth; Fig. 3b), indicating the presence of shallow bedrock (which partially emerges in the escarpment border, cf. Fig. 1).

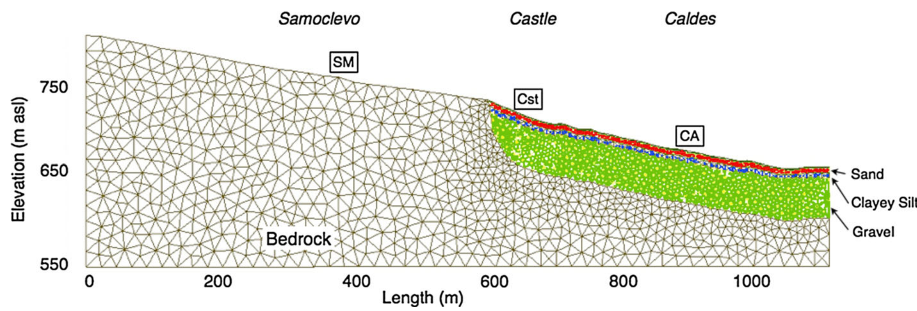

Fig. 7 2D mesh of the resumed subsoil model for the Caldes slope. Seismic bedrock (*gray*), sand (*red*), clayey silt (*blue*) and gravel (*green*) are distinguished. SM, Cst and CA stand for Samoclevo, Castle and Caldes sites, respectively

Shear-wave velocity values of the Caldes slope site are within the typical ranges of sands, silts, and gravels (from 200 to 480 m s^{-1}; e.g., Eurocode 8 soil classification). This is in agreement with the depth distribution of borehole data granulometry. The MASW technique confirms the absence of seismic bedrock at its maximum depth of investigation (about 40 m, Fig. 4c). The FTAN technique (Nunziata et al. 1999) is able to obtain reliable deep subsoil reconstructions and is considered an efficient tool complementary to multi-channel methods, especially to investigate deeper subsoil levels. At the Caldes site, FTAN provided deeper information than MASW, even if with lower resolution, suggesting the presence of high velocity seismic bedrock ($V_s > 800$ m/s, e.g., Eurocode 8) at 54 m depth (Fig. 4d). MASW and FTAN methods are in general agreement characterizing the Caldes soft sediments at shallower depth. Both techniques suggest V_s in the range of 200–315 m s^{-1} (typical values for silty and sandy materials) down to 15 m of depth and V_s values up to 420–480 m s^{-1} at greater depths (typical velocities of gravels).

Microtremor analysis yields the resonance frequencies of the alpine slope. Since V_s is known from surface wave analysis, passive seismic results can be used to estimate the depth of main impedance contrast at the interface between the seismic bedrock and soft sediments. It must be underlined that 2-D resonance and surface wave can affect microtremor analyses in cases of complex topography. These effects, affecting HVSR measurements, were however not expected for the case of the Caldes valley, considering the typical literature criterion for thickness-width relationship (Bard and Bouchon 1985; Guillier et al. 2006; Bonnefoy-Claudet et al. 2009). All HVSR measurements at Caldes (HVSR1–3) were carefully checked and reveal in fact a clear narrow peak with no evidence of a plateau-like or a small amplitude broad peak (Bonnefoy-Claudet et al. 2004). Moreover, the directional analysis of the seismic noise highlighted omni-directional properties without oriented sources. HVSR results along the slope gave a resonance frequency in the range of 1.7–3.0 Hz (Fig. 5a, b, c). A direct modeling of subsoil frequency responses (cf., Castellaro and Mulargia 2009) estimated the depths of the main impedance contrasts. These are located at about 44, 51, and 60 m depth for the 3 measurements points (HVSR1–3, Fig. 5a, b, c), in good agreement with the results of the other geophysical techniques. HVSR4 measurement at Samoclevo, on the contrary, did not present any resonance peak evidence (Fig. 5d), suggesting the absence of strong impedance contrast. It can be related to very shallow seismic bedrock, as already shown by electric tomography and geological survey (the bedrock partially emerges in the escarpment which borders the 'Samoclevo' slope, Fig. 1).

Table 1 Subsoil parameters for the Caldes site (cf., Figs. 1, 2) derived from borehole data and geophysical results

Depth (m)	V_s (m/s)	Geological material
0	258.0	Sand
1	253.3	
2	227.3	
4	191.7	Clayey silt
6	203.5	
8	251.7	
10	312.1	Gravel
13	365.8	
16	406.7	
21	430.4	
26	443.5	
31	450.6	

All of the geophysical results are summarized in the 2D model of the slope (Fig. 7) from the integration of the experimental data and the geological/geotechnical knowledge, both in terms of geometry and geological material distribution. In the final model, strata with similar velocities were grouped to obtain a computationally reasonable number of geological layers and associated materials (Table 1). Clearly visible in Fig. 7 is the sharp and partially unexpected transition between the northern slope part (Samoclevo, SM) and the southern one (Caldes, CA), where the medieval Castle (Cst) is located.

Table 2 List of the seven earthquake accelerograms selected using the REXEL code (Iervolino et al. 2010) as input for response calculations

Date	Earthquake name	M_W	Fault mechanism	Epicentral distance (km)	PGA (m s^{-2})
25.05.1987	Mt. Vatnafjoll	6.0	Oblique	42	0.131
13.10.1997	Kalamata	6.4	Thrust	61	0.205
13.10.1997	Kalamata	6.4	Thrust	103	0.126
13.10.1997	Kalamata	6.4	Thrust	48	1.146
30.04.1985	Anchialos	5.6	Normal	55	0.193
18.11.1997	Strofades (aftershock)	6.0	Strike-slip	93	0.105
18.11.1997	Strofades (aftershock)	6.0	Strike-slip	93	0.115

Seismic local response analysis

Local site seismic response analyses evaluate the specific contribution of soil to the ground motion at the surface. For this purpose, we need to specify (1) depth of the seismic bedrock (usually defined as a material with $V_s > 800$ m/s, see Eurocode 8), (2) number and thickness of soil layers overlying the bedrock, and (3) the material properties and seismic velocities of bedrock and soil layers (unit weight, V_s, dynamic properties). Accelerometric time-histories are used as input ground motions. Here, we adopted both 1D and 2D equivalent linear approaches, as described below.

Earthquake input selection

According to the Italian building code (Gruppo di Lavoro 2008), we selected 7 input seismic recordings. The selected records were scaled to approximate the elastic response spectrum at the site using the REXEL code (Iervolino et al. 2010) to define the target spectra in agreement with the Italian Norms. Record compatibility was also verified in terms of seismogenic source (e.g., magnitude and epicentral distance), ground motion intensity, and soil conditions. In particular, moment magnitudes are comprised between 5.6 and 6.4, while epicentral distances are in the ~40–100 km range (Table 2). Selected faulting mechanisms were chosen of different types, because this seismotectonic area does not have a clearly recognized dominant style of faulting (Viganò et al. 2008, 2013) (Table 2). Target spectra were determined as reported in the Online Resources.

Linear equivalent 1D and finite element 2D simulations

For the linear equivalent 1D analysis, we adopted the EERA code (Bardet et al. 2000), based on the Kelvin–Voigt physical model (continuous and homogeneous layers with linearized viscoelastic behavior). This method considers the non-linear soil behavior through the shear modulus and damping ratio curves and obtaining solutions via an iterative procedure. The choice is justified in our case study because of the relative low seismicity of the lower Val di Sole alpine slope. Each soil layer is considered homogeneous and isotropic and is characterized by its thickness, density, shear modulus, and damping ratio.

For the 2D approach, we used instead the 2D QUAD4 M code (Hudson et al. 1994), which can consider 2D geometries and topographical effects. The code operates in the time domain and is based on the equivalent nonlinear constitutive law for materials.

Results and discussion

Figures 8 and 9 summarize the results in terms of horizontal response spectra for the selected sites along the slope: Samoclevo, Castle, and Caldes (SM, Cst, and CA in Fig. 7). Figure 8 shows the 1D and 2D analysis response spectra for all of the 7 compatible inputs for the Samoclevo and Caldes sites. Figure 9 instead shows all of the average response spectra for all three sites (SM, Cst, and CA). The results are compared to the design spectra from the National Italian a-seismic code regulation, where Samoclevo and Caldes are classified as type A and type C seismic soils, respectively, ($V_{s,30}$ parameter characterization, in accordance with Italian Norm and Eurocode 8).

At Samoclevo, where the bedrock is very shallow, response spectra mainly agree with the reference soil A spectrum for both 1D and 2D calculations (Fig. 8). On the contrary, at Caldes, the modeled accelerations can reach values considerably higher than the reference soil C spectrum (about 0.4 or 0.5 g for 1D and 2D models, respectively, with respect to the 0.2 g reference value; Fig. 8). In Fig. 9a, we can observe for the Samoclevo site, very good agreement between average acceleration spectra both from 1D (EERA) and 2D (QUAD) approaches with the reference Norm spectrum. At the Castle site, where the simplified 1D approach cannot be used due to its unusual bi-dimensional character, the 2D average response is less conservative than the soil C Norm reference (Fig. 9b). At the Caldes site, the 2D response shows a severe scenario with acceleration

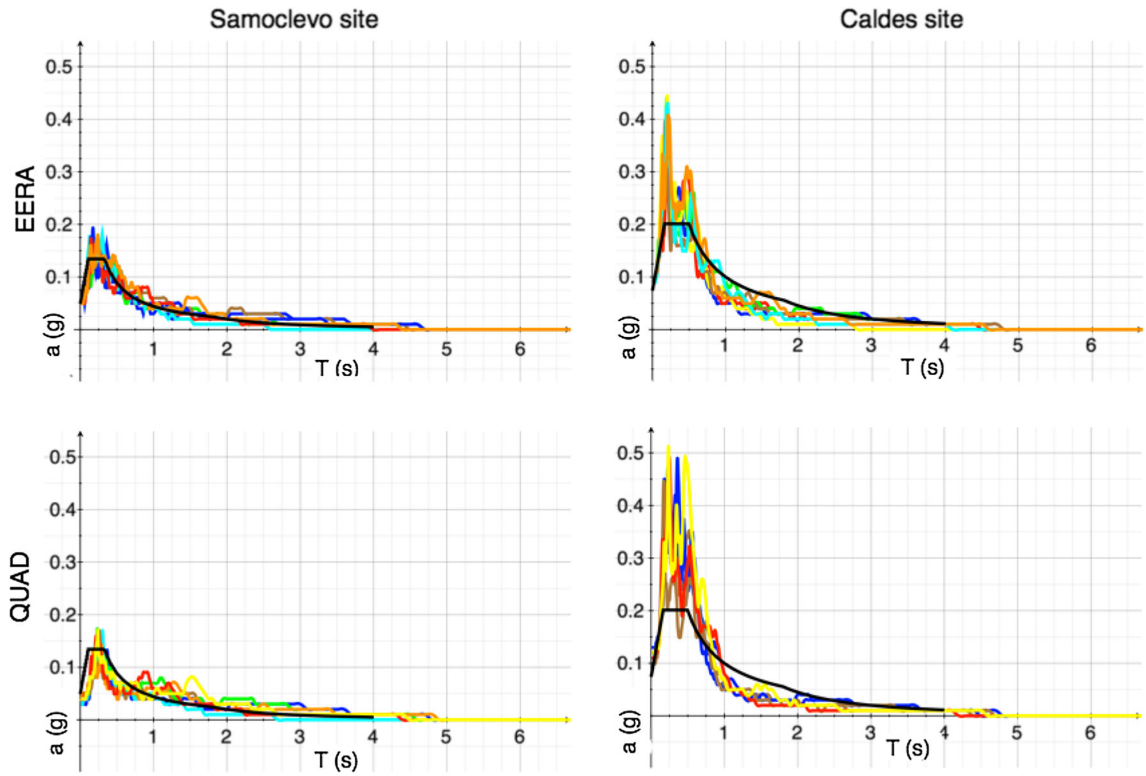

Fig. 8 Earthquake response spectra for the Samoclevo (*left side*) and Caldes (*right side*), resulting from 1D calculations (EERA code, *top panels*) and 2D approaches (QUAD code, *bottom panels*). Colored response spectra refer to the 7 compatible adopted seismic inputs adopted, while Italian Norm spectra for a soil type A (Samoclevo) and C (Caldes) are in *black*

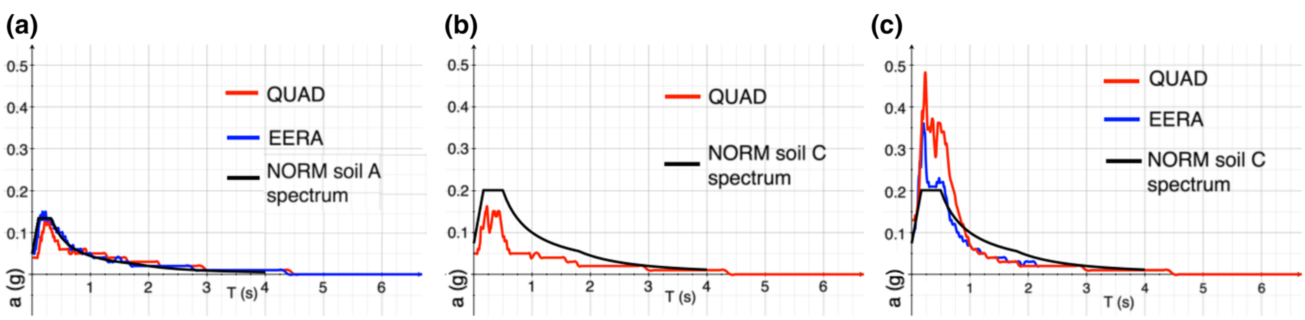

Fig. 9 Comparison between average *horizontal* response spectra for 2D analysis (*red*), 1D analysis (*blue*) and reference Norm (*black*). **a** Samoclevo, **b** Castle, **c** Caldes (cf., SM, Cst and CA in Fig. 7)

peaks (about 0.45–0.50 g in the 0.2–0.8 s period range), with an increment of about 25 % with respect to the 1D model (about 0.35 g of maximum acceleration) (Fig. 9c). The results obtained at Caldes do not vary significantly for points located along the model section close to point Ca in Fig. 7 due to a laterally uniform lithological amplification effect. Here, the range of periods corresponding to the maximum amplification (both 1D and 2D cases) includes the typical natural frequencies of vibration for buildings of urbanized mountain sites (e.g., masonry buildings, Kramer 1996).

Despite the limited extension of the model area, between the mountain slope and the middle valley (Fig. 2), the presented seismic analyses show a significantly varying seismic response between the two close sites of Samoclevo and Caldes. This is mainly due to the different distribution of soft sediments (variable thickness) and the complex deep valley structure (depth of the seismic bedrock). In fact, a buried steep rocky scarp (verified by field observations) delimits the northern and southern slope portions. This bedrock scarp, despite its clear evidence from geological and Digital Terrain Model (DTM) maps (cf. Figs. 1, 2), could be easily misinterpreted in terms of deep geometry and material properties. Similarly, the very limited soil thickness (<3–4 m) at the Samoclevo southern limit was unexpected. In any case, we suppose the presence of thick sediments upward (debris-flow fans), close to the mountain flank in the upper Samoclevo town (cf., Fig. 1).

All of the results from the geophysical techniques applied here allowed us to construct a clear seismo-stratigraphic model. In particular, passive microtremor surveys yielded quick first-order appropriate information for the reconstruction of buried impedance contrasts (according to Field and Jacob 1993; Le Roux et al. 2012). The best-solution model from geophysical measurements was selected considering the lowest misfit error in the inversion process between experimental data and theoretical models. However, each geophysical method involves measurement uncertainties that variably contribute to constrain the model and its uncertainty also. In this way, we tested the reliability of the calculated seismic responses considering different models. In particular, we considered the model uncertainties about the seismic velocity distribution (V_s profiles) and calculated different responses including a ± 20 % variation of V_s values for each seismo-stratigraphic layer (not shown). Two end-member models were built, maximizing (or minimizing) at the same time all of the assigned velocities (cf., Table 1). The resulting seismic response spectra do not differ more than ± 8 % (in terms of peak acceleration) with respect to those shown in Figs. 8 and 9. For this reason, for the Caldes case study, the assumed V_s uncertainty does not seem to play a critical role in the local response results.

Conclusions

A subsoil model for a typical urbanized mountain site (Caldes, NW Trentino region, Italy) has been presented. The best-solution seismo-stratigraphic model was obtained by integrating in situ geophysical investigations with geological data. The seismic response analyses were calculated also using specifically calibrated geotechnical laboratory measurements. The main points are summarized below.

- The observed lateral heterogeneity of subsoils along the Caldes slope, especially in terms of bedrock geometry, supports the need to make direct investigations also at small scales (the length of the alpine slope under study is only ~1000 m). In fact, possibly unexpected subsoil structures and/or variations in seismic properties, if not correctly considered, can lead to severe misinterpretations for seismic shaking.
- The seismic shaking observed along the Caldes alpine slope (2D model) yields maximum accelerations (up to ~0.4–0.5 g) where the sedimentary cover is thicker (50–60 m), while at the border of the sediment infilling (Castle site), accelerations are slightly lower than the reference Italian Norm spectrum (C soil category; ~0.15 g). A variation of ± 20 % of the shear-wave velocities assigned to each seismo-geological layer implies a maximum ± 8 % variation of the acceleration peaks on the response spectra. This demonstrates that uncertainty in V_s measurements is common and tolerable in terms of ground acceleration characterization. The comparison of different approaches revealed that the difference between 2D and 1D analyses are relevant in the case of the mountain slope studied. Especially for mountain slopes where sediment thickness is not negligible, the use of the 1D linear equivalent approach or the $V_{s,30}$ based simplified procedure should be discouraged.
- Accurate 2D modeling is mandatory for the mountain slope context because both 1D simulations and the simplified approaches based on the $V_{s,30}$ characterization (Eurocode 8 and Italian Norms) can significantly underestimate acceleration responses (down to about 2 times), especially for areas of local engineering interest (masonry buildings).
- Shaking modeling software and real acceleration histories are today largely available for the scientific and technical communities. However, for a complete and realistic seismic response, a coherent and robust physical (i.e., seismo-stratigraphic) model is necessary, which generally can be obtained by a site-suited multidisciplinary analysis.

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