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On the role of stiff soil deposits on seismic ground shaking in western Liguria, Italy: Evidences from past earthquakes and site response

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ABSTRACT

In this work, we analyze the macroseismic fields of the main historical earthquakes occurred in western Liguria (northwestern Italy) in order to identify possible relations between the isoseismal patterns and the local geological setting. Anomalies in the spatial distribution of macroseismic intensities are often attributed to site effects. We observed that, in the region of study, such anomalies are mainly located in areas characterized by outcropping Pliocene soil deposits, mainly made up of stiff silty and marly clays. To investigate the influence of such deposits on ground response, both horizontal-to-vertical spectral ratio measurements and numerical site response analyses were carried out. For all sites analyzed, the spectral ratio curves show marked amplification peaks between 2 and 5 Hz. Following such empirical evidence, equivalent linear ground response analyses were performed in order to examine the relation between the measured resonance frequencies and the response of a set of soil columns presenting Pliocene marly-clayey deposits at their top. To this end, a database of geotechnical and geophysical properties, including > 50 reference soil profiles, was compiled. This database was used to define alternative numerical models considering three different ranges of thickness of the Pliocene marly-clayey deposits (between 5 and 35 m, 30 and 65 m, 60 and 105 m). Results show marked amplification effects in the ranges 1–3 Hz, 2–5 Hz, and 3–10 Hz depending on the thickness of the investigated soil deposits. These frequency ranges are in agreement with those observed from the experimental measurements, which are therefore proved adequately representative of the resonance frequencies of the Pliocene marly-clayey deposits. Therefore, based on our findings, such deposits can be considered an essential factor in producing the "anomalies" observed in the isoseismal patterns of the macroseismic fields of the historical earthquakes occurred in western Liguria.

1. Introduction

The distribution of the total economic and human losses produced by a strong earthquake may be related to both seismological and engineering factors. While the former are inherent to the earthquake characteristics, such as source properties (e.g., rupture process, fault geometry) and seismic wave propagation between the source and the earth surface, the latter depend on the structural features and the asset exposure. Near-surface geological conditions represent the link between these factors. On the one hand, geology may affect the seismic motion by modifying its frequency content, amplitude, and duration. On the other hand, the modifications to the ground motion caused by local geology may affect the dynamic behaviours of the buildings exposed to the seismic shaking and, consequently, the total losses produced by an earthquake. The effects of local geology, which can be incorporated into probabilistic seismic hazard analyses (e.g., Bazzurro and Cornell, 2004; Rodriguez-Marek et al., 2014; Barani et al., 2014; Barani and Spallarossa, 2016; Barani et al., 2016), are commonly termed as site effects. In areas characterized by complex geomorphology and/or particular soil conditions (e.g., sites characterized by soft soils overlying rock formations), the definition of site effects represents one of the most important issues of seismology and earthquake engineering (e.g., Massa et al., 2004; Gallipoli et al., 2004; Parolai et al., 2010; De Ferrari et al., 2010; Edwards et al., 2013; Massa et al., 2014; Massa et al., 2016; Mascandola et al., 2017). Site effects can be examined either through experimental methods or by using numerical approaches. Experimental methods consist of computing spectral ratios of earthquake recordings relative to a reference site (Borcherdt, 1970) or to the vertical component of the same recording at a single station (Lermo and Chavez-Garcia, 1993). When horizontal-to-vertical spectral ratios (HVSRs) are based on ambient noise recordings, the technique is known as Nakamura's method (Nakamura, 1989). Numerical approaches simulate the dynamic behavior of soils and, depending on the local geomorphological features to be modeled, can be distinguished into mono- or multi-dimensional methods (Kramer, 1996).

The application of site response methods may be guided by the

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knowledge of local geology or by the analysis of the damage distribution produced by past earthquakes, which is often influenced by site effects. For instance, De Ferrari et al. (2010) applied both experimental and numerical methods (1D and 2D) in order to corroborate the hypothesis of ground shaking amplification deduced by the analysis of the macroseismic field of the 1920 Garfagnana earthquake (moment magnitude $M_w = 6.5$). D'Amico et al. (2002) validated the same anomalies through HVSR measurements.

This study was prompted by observation of "anomalies" (i.e., sites with intensities of at least one degree greater than surroundings) in the macroseismic fields of the strongest historical earthquakes occurred in western Liguria (e.g., 1564 earthquake with $M_w = 5.8$, 1831 earthquake with $M_w = 5.6$, 1854 earthquake with $M_w = 5.7$, 1887 earthquake with $M_w = 6.3$, 1963 earthquake with $M_w = 6.0$ (Locati et al., 2016)) and the knowledge of the regional distribution of Pliocene deposits, thus suggesting a possible relationship between them. In light of this evidence, this study investigates the role of some Pliocene deposits, which mainly consist of stiff marly clays, on seismic amplification through the application of experimental and numerical site response methods. Amplification effects related to stiff soil deposits, such as those just mentioned, are poorly documented in literature. Only few authors focused on this issue starting from the observation of irregular damage patterns (e.g., Bouckovalas and Kouretzis, 2001; Lekkas, 2001). Furthermore, since current anti-seismic codes give special emphasis to soft soils, the role of stiff soils or weak rocks on ground motion amplification may be overlooked. In western Liguria, many towns and settlements are built on Pliocene marly-clayey deposits. Moreover, some of the populated areas are characterized by high density of inhabitants enhancing the seismic risk. It is therefore evident the importance of investigating the seismic behavior of such materials in order to outline future seismic risk mitigation strategies.

This paper first presents a brief overview of the historical seismicity of western Liguria, examining correlations between the geographic distribution of macroseismic anomalies and that of Pliocene stiff marly-clayey deposits. Subsequently, geotechnical data and spectral ratio measurements are described. Results of such measurements are then compared with the response of a set of typical stratigraphic settings of Pliocene clayey soils, which is evaluated through 1D numerical ground response analyses. The goal of our study is twofold. On the one hand, it allows attaining a better knowledge of the seismic behavior of the Pliocene stiff marly-clayey deposits. On the other one, it allows verifying their influence on the anomalies observed in the macroseismic fields of historical earthquakes occurred in the study region.

2. Data and methods

2.1. Evidences of macroseismic anomalies

Western Liguria is one of the seismically most active regions in northwestern Italy (e.g., Barani et al., 2010). It is characterized by moderate seismicity, both distributed in well defined onshore areas and along the main active faults in the Ligurian Sea (e.g., Barani et al., 2007; Scafidi et al., 2015). As observed above, moderate magnitude earthquakes have occurred in the past, the largest one with magnitude 6.3 on February 23, 1887 at 5:21 a.m. (UTC time). Analyzing the distribution of the felt intensities produced by this earthquake (Locati et al., 2016), the largest damage and losses were concentrated in municipalities where Pliocene deposits crop out (Fig. 1). For instance, the intensity value associated with Diano Castello (purple circle in Fig. 1) is equal to X MCS (Mercalli-Cancani-Sieberg), which results two-to-three degrees greater than the one associated with the surrounding municipalities like Varcavello and Diano San Pietro, where the intensities reached VII and VIII MCS, respectively (see Fig. 1). Similar anomalies are observed for Bussana Vecchia (IX), Pompeiana (VIII–IX), and Vallecrosia (VIII): at these sites, the observed intensities are one-to-two degrees greater than those associated with the surrounding municipalities. Macroseismic anomalies also emerge from the macroseismic fields relative to other significant earthquakes occurred in western Liguria. For instance, the macroseismic fields of the 1831 ($M_w = 5.6$) and 1854 ($M_w = 5.7$) earthquakes (see at http://emidius.mi.ingv.it/CPTI15-DBMI15/) again show intensities that, at the site of Bussana (VIII MCS and VII-VIII MCS, respectively), are generally greater, by about one-to-two degrees, than those observed in the surroundings (between VI and VII MCS). In addition, also the site of Castellaro, which is located about one kilometer west of Pompeiana, presents an intensity that is unexpectedly higher compared to those associated with the surrounding sites in the macroseismic field of the 1831 earthquake. At this site the CEDIT catalogue (Martino et al., 2014) reports a slope failure induced by this earthquake.

Interestingly, the macroseimic anomalies observed at the previous sites correlate well with the geographical distribution of the Pliocene stiff clayey soils. This is interpreted as a hint of site effects, which will be discussed in the following.

2.2. Geologic framework

In the Liguria region, Pliocene deposits only crop out along the western coast between the city of Genova and the Italy-France border (Fig. 1). Since the second half of the last century, these Pliocene sediments have been exhaustively studied by a great deal of researchers in order to understand their stratigraphic, sedimentological, paleontological, and structural features (Capponi et al., 2008; Giammarino et al., 2010). The Liguria Pliocene deposits are considered a post-orogenic sedimentary cover. They are usually trapped in East-West or North-South trending fault-controlled basins, which are interpreted as grabens. These tectonic structures are related to the Plio-Quaternary tectonic up-lift, which involved a large part of the Ligurian coast after the main phases of both Alpine and North Apennine orogens. Therefore, tectonic events played a key role in controlling the evolution of the Liguria Pliocene sedimentation. These extensional tectonic events led to a continental margin morphology characterized by structurally controlled lows (grabens) filled by sediments and highs (horsts) affected by rapid dismantling. Such structural evolution is also clearly recognizable in the continental shelf of the Ligurian Sea.

The Pliocene succession has a maximum thickness of about 450 m (Marini, 2001) and unconformably overlies a substratum characterized by different rocks. Along the western and eastern coastal sectors of the considered area, the bedrock generally consists of Cretaceous to Eocene turbidite complexes (Pepe et al., 2015). Conversely, along the stretch comprised between the towns of Genova and Savona, the Pliocene deposits overlay the metamorphic belt of the Ligurian Alps (metaophiolites, meta-acidic volcanics, and metasediments) (Crispini and Capponi, 2001; Carobene and Cevasco, 2011).

The Liguria Pliocene deposits are currently grouped into two lithostratigraphic formations (bottom to top): the Argille di Ortovero Fm. and the Conglomerati di Monte Villa Fm.. The former consists of compact deep marine marly clays (up to 150 m thick) with siltstone and fine sandstone bodies interbedded. The latter (with maximum thicknesses of about 300 m) groups a number of deep sea fan-delta coarse-grained clastic deposits. Based on paleontological content, the Pliocene deposits generally date back to the Lower Pliocene. However, sedimentary bodies attributable to the Upper Pliocene-Lower Pleistocene are also reported. The Argille di Ortovero Fm. is widely spread over all the considered study area. Conversely, fan-delta bodies only crop out in the westernmost sector.

2.3. Geotechnical classification

Based on results of laboratory tests (i.e., grain size analyses, Atterberg limits, and physical determinations) collected from technical reports of civil engineering projects, the investigated materials were classified according to the Unified Soil Classification System (USCS).