**AN INTER-DISCIPLINARY AND MULTI-SCALE APPROACH TO ASSESS THE SPATIAL VARIABILITY OF GROUND MOTION FOR MICROZONATION PURPOSES: THE CASE STUDY OF CAVEZZO MUNICIPALITY IN THE PO PLAIN (ITALY)**

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**ABSTRACT**

In July 2017, an inter-institutional agreement was signed between the University of Pavia, Eucentre, the administration of Emilia-Romagna Region, the Province of Modena and the Municipality of Cavezzo to perform a microzonation study at the town of Cavezzo (Modena, Northern Italy). This research study was led as part of the European H2020 project LIQUEFACT, initiated in May 2016 with the main goal of establishing guidelines for the assessment and mitigation of damages to structures and infrastructures caused by earthquake-induced soil liquefaction. Within this framework, the municipality of Cavezzo was selected, among four European testbed territories, as case-study for mapping the liquefaction hazard at urban scale that is for preparing a microzonation chart.

In this paper we discuss the work carried out in Cavezzo to characterize the spatial variability of ground motion amplification due to local ground conditions. A multi-disciplinary approach is presented, involving geotechnical engineers, geophysicists, geologists and seismologists from different institutions with the goal of thoroughly characterizing the territory at different scales and different level of confidence. Geomorphological, geological, hydrogeological, seismological, geotechnical and geophysical investigations were carried, with a special focus on the mapping of uncertainties. A GIS-based (Geographic Information System) platform was setup to manage the collected data, which now includes the results of more than 1,000 geotechnical and geophysical tests. Such extended dataset allowed the definition of a geotechnical and a seismo-stratigraphic model of the territory, used as input for linear-equivalent ground response analyses.

1. **INTRODUCTION**

The Seismic Microzonation (SM) is the process that aims at identifying and mapping the subsoil local seismic response in a given territory (typically an urban area). This is done in terms of both selected ground shaking intensity parameters and susceptibility to ground instabilities. Guidelines for seismic microzonation were issued by Emilia-Romagna region in 2015 (DGR n.2193) to support territorial and urban planning. These guidelines establish criteria and operational instructions for the identification of areas subject to site effects and for seismic microzonation in order to guide planning towards areas characterized by lower seismic hazard. Three levels of investigation are identified.

Level 1 is the preparatory level for the SM studies and aims at identifying areas susceptible of site effects (i.e. ground motion amplification, slope instability, soil liquefaction, ground fractures, etc,…); it relies on the collection of existing data, which are processed to divide the investigated area into zones that are qualitatively homogeneous in a seismic perspective. Level 2 is a simplified SM; it defines site effects with a quantitatively evaluation of amplification factors using geophysical information and ad hoc amplification’s tables (abacus) in PGA and spectral intensities. Level 3 is a detailed SM that requires in situ investigations and ground response numerical analysis.

[stato dell’arte, introduzione al progetto LIQUEFACT e contestualizzazione, motivazione del lavoro svolto]

1. **GEOLOGICAL AND SEISMOTECTONIC SETTING**

The study region is located within the western margin of the Po plain, a large foreland sedimentary basin originated by the progressive convergence of the Africa/Adria and Eurasia plates initiated during the late Cretaceous and still ongoing. Such compressional regime led to the development of large thrust and folds structures with roughly WNW-ESE trending, but of opposing vergence to the North and to the South of the longitudinal valley axis. Some of the southern buried structures have demonstrated to be still under active shortening, causing non-negligible past seismicity, whose noticeable expression was the recent 2012 Emilia sequence.

The sedimentary infill of the Po plain consists of a thick sequence of sediments of Tertiary-Quatertiary age, from fine Pliocene muds to more course silt, sand and gravel alternations due to transition to continental deposition from the Pleistocene. Depositional sequence is heavily disturbed by the ongoing deformation process and the alternation of episodes of erosion and glaciation, which have generated several noticeable angular unconformities and gaps (Mascandola et al. 2019).

[manca una parte della geologia di superficie]

1. **METHODOLOGY**

Starting from the GIS database, a lithological model was constructed from boreholes and CPT results. Then, homogeneous areas identifying the major lithological units (LU) were outlined. Next, stratigraphic vertical cross sections were developed oriented longitudinally and transversally with respect to the main geomorphological features. A 3D geological model was constructed for the territory under study down to a depth of 30 m and for an area of approximately 27 km2.

A large-scale seismo-stratigraphic pseudo-3D model was then developed based on the data acquired from the geophysical surveys. At this purpose, advance geophysical processing techniques were used, such as the combined inversion of multi-component surface wave datasets based on a joint interpretation of travel-time, dispersion and polarization data. This has led to the definition of different realizations of 1D seismo-stratigraphic profiles at each of the 2,984 nodes of a grid with a 0.001 degrees spatial resolution (about 100 meters) covering the Cavezzo territory. Overall, 11 complementary seismo-stratigraphic models were defined at each of the 2,984 nodes. The resulting 3D model has then been used for the calculation of the seismic amplification factors through ground response analyses taking into account the epistemic uncertainty associated to the input models.

More specifically, at each of the 2,984 nodes and for each of the 11 seismo-stratigraphic models, 1D ground response analyses were carried out using the linear-equivalent soil constitutive model. The input motions referred to outcropping bedrock conditions were defined for 475, 975, and 2475 years return periods in terms of suites of 7 seismo- and spectrum-compatible real accelerograms. For each return period, 229,768 analyses were carried out considering 2,984 nodes, 11 seismo-stratigraphic models and the 7 accelerograms. Results have been finally combined in a logic-tree approach to better depict the epistemic variability in the ground motion amplification associated to the uncertainties in the definition of the 3D seismo-stratigraphic model and the variability of reference input motion.

1. **GROUND CHARACTERIZATION**

The territory of Cavezzo was thoroughly characterized from different viewpoints, i.e. geomorphological, geological, hydrogeological, seismological, geotechnical and geophysical.

* 1. *Geotechnical and geophysical ground investigations*

As starting point, existing data retrieved from trench pits, boreholes, piezometric, in situ and laboratory geotechnical and geophysical investigation campaigns were collected. Figure 1a shows the existing data available for ground characterization of the territory of Cavezzo before the LIQUEFACT project started. Based on the quality and quantity of the retrieved existing data, then, complementary ground investigation campaigns were purposely devised.

In-situ ground investigation included cone penetration tests with acquisition of the excess pore pressure (CPTu) and the shear wave velocity Vs (SCPTu), standard penetration tests (SPT) and the drilling of boreholes. Laboratory tests were also performed on undisturbed samples retrieved with the gel-push technique (Cubrinovski et al., 2016). Furthermore, a number of non-invasive geophysical tests were performed including multi-channel analysis of surface waves (MASW), single-station and 2D array measurements of ambient vibration, high-resolution seismic reflection (P and S) and 3D electric tomography. Geophysical prospecting allowed illuminating large volumes of soils while providing a mean to correlate the results obtained at different locations from the conventional geotechnical tests.

All data gathered on the subsoil of Cavezzo were organized into a purposely-developed GIS database, which now includes the results of more than 1,000 geotechnical and geophysical tests, as shown in Figure 1b. Data of both 1m and 5m resolution DEM were also included.

* 1. *Processing*

[array ?]

1. **SOIL MODEL IMPLEMENTATION**
   1. *Seismo-stratigraphic soil model*

The seismo-stratigraphic soil model has been implemented by integrating information from the processing of active and passive seismic data, either already available from previous studies (mostly MASW) and from new ad-hoc investigations on the target area. For these last, in particular, fundamental was the contribution of the National Institute of Geophysics and Volcanology (INGV Milano) and the National Institute of Oceanography and Applied Geophysics (OGS, Trieste), who respectively led the ambient vibration and the P/S reflection seismic acquisition campaigns.

Assuming a relatively smooth variability of the geophysical properties of the soil across the area, the pseudo-3D model has been initially implemented starting from a set of velocity of velocity models obtained from a single target site, chosen as sufficiently representative (on average) of the investigated region. A set of 11 velocity profiles were selected, obtained by combining the results from the inversion of surface wave dispersion information from array analysis of ambient vibrations (hereinafter the EUCENTRE model) and from the processing of reflection seismic data (OGS model). The two techniques have shown to produce consistent results down to about 100m depth, while some deviations were observed at larger depths. Such discrepancy has been considered as epistemic variability of the reference velocity models, and accounted in the following processing by means of a logic-tree approach.

In a subsequent step, for each point of the 3D model the reference profiles have been adjusted to match the observed variability of both the shallow subsoil conditions and of the deepest resonating layer interface (assumed to be the local geophysical bedrock). A map of the surface velocity variability was obtained by interpolation of Vs30 estimates from 83 previous MASW analysis. It must be noted that being the results from MASW data quite heterogenous (e.g. obtained from different surveys and using different processing schemes), we decided to homogenously reassess the Vs30 of each measurement by means of a simplified procedure as proposed by Brown et al. 2000 and further developed by Martin & Diehl 2004 and Albarello & Gargani 2010 (see also Comina et al. 2011 for clarifications). In practice, the Vs30 of a site was obtained empirically from the Rayleigh wave dispersion curve by extracting the phase velocity corresponding to a wavelength (λ) in a range between 35 and 45 m. In this study we used a λ of 40m, which provided estimates of Vs30 comparable with those obtained from independent processing. Spatial interpolation of the Vs30 values was performed using Ordinary Kriging.

Complementary, the geophysical bedrock was obtained by inversion of the fundamental frequency of resonance (f0) from horizontal to vertical ratio analysis of 26 single station ambient vibration recordings sparse on the area. Consistently with the procedure used to map shallow velocity variability, spatial interpolation between measuring points was performed using Ordinary Kriging.

* 1. *Identification of the major lithological units*

To carry out ground response analyses, an accurate knowledge of the geotechnical characteristics of the subsoil of the site is required. Based on joint analysis of stratigraphic, lithological and geomorphological informations the municipality of Cavezzo was divided in homogenous area.

9 different stratigraphy shallow geological models have been defined based on joint analysis of stratigraphy from boreholes and water well and from stratigraphic interpretation of CPTu/CPT tests. These areas divide the territory in homogenous zones from lithological and genetic depositional environment point of view (Figure 2). For the stratigraphic interpretation from CPTu/CPT data was used a correction of Soil Behaviour Index (Ic Robertson 2009) calibrated based on CPTu tests and boreholes (Meisina et al 2019) in order to identify the mixture layers falling within the transition zone of reference chart (Robertson, 2009).

* 1. *The seismic-geotechnical model*

The seismic-geotechnical model was defined starting from pseudo-3D seismo-stratigraphic model (§3.1), in detail, the model has been defined starting from 10 versions of INGV model, which were associated a weight equal to 0.5) and the OGS model (which was associated a weight equal to 0.5). Each model was characterized from 2984 monodimensional (1D) Vs-profiles, located on a reference grid that covers the territory of Cavezzo municipality. A total of 32824 models (2984x11) have been defined. In order to define the seismic-geotechnical model necessary to perform ground response analysis, the properties defined in geophysics model have been merge to stratigraphic information related to geological model. In detail, 9 homogeneous areas showed in 3.2 were used considering the uncertainty associated. For each homogeneous area, the points of the reference grid falling within its boundaries have been identify and for each layer of 11 geophysics models, a statistical analysis of thickness values was been performed. The assessment of local stratigraphic site effects was performed by 1D linear-equivalent analysis using an in-house SHAKE91-based code. An ad-hoc calibration has been performed for the definition of shear modulus and damping ratio decaying curves as proposed by Darendeli (2001) using data from laboratory tests performed in December 2017 in Southern area of Cavezzo municipality (Figure 4). For each return period, 229,768 analyses were carried out considering 2,984 nodes, 11 seismo-stratigraphic models and the 7 accelerograms. Results have been finally combined in a logic-tree approach to better depict the epistemic variability in the ground motion amplification associated to the uncertainties in the definition of the 3D seismo-stratigraphic model and the variability of reference input motion.

1. **MICROZONATION**
   1. *Definition of the reference seismic input*

The seismic hazard at the site under examination was determined, for the three considered return periods (475, 975 and 2475 years), in terms of elastic acceleration response spectra referred to rigid ground conditions, and seismo- and spectrum- compatible natural accelerograms.

The elastic response spectra were computed according with the prescriptions of the previous Italian seismic code (NTC, 2008). Table 1 summarizes, for each considered return periods, the values of the parameters necessary to define the elastic response spectra for soil class A with reference to the Municipality of Cavezzo: ag is the horizontal peak ground acceleration on a horizontal rigid reference site, F0 is the maximum value of the amplification factor of the horizontal acceleration spectrum and TC\* is the upper limit of the period of the constant spectral acceleration branch.

For each return period, a group of 7 independent accelerograms recorded on free-field rock ground conditions, spectrum-compatible with the elastic response spectrum defined by the NTC (2008) for the municipal territory of Cavezzo was selected. The selection was made using an updated version of the program ASCONA (Corigliano et al., 2012), which provides a set of strong motion recordings satisfying several criteria (e.g., magnitude and distance ranges, spectral shape), with the additional requirement of compatibility with a target spectrum (in this case, the elastic acceleration response spectrum prescribed by the Italian code in force), in a specified period interval (in this case, from 0.15 s to 2 s). Regarding signal scaling, the PEER (2010a, 2010b) approach was used. Among the different accelerogram sets that satisfy the requirements, the set returned by ASCONA is the one characterized by the minimum average deviation of the average response spectrum (of the 7 accelerograms) with respect to the target spectrum.

* 1. *Ground response analysis*

One-dimensional local seismic response analyses were carried out for Cavezzo using the SHAKE91 code (Schnabel et al., 1972; Idriss and Sun, 1992). The analyses were conducted for 3 return periods, 7 accelerograms, 2,984 points of the reference grid for which the geotechnical-seismic model P3D was defined and 11 models, for a total of 229,768 analyses. For each analysis, amplification factors (Fi) in terms of peak ground acceleration, Housner intensity ratio (computed for four different period intervals) and acceleration response spectrum integral ratio computed in the spectral interval between 0.1s and 0.5s were computed. For each node of the grid and each return period, the Fi values computed from the 7 accelerograms and 11 models were averaged as follows:

|  |  |
| --- | --- |
|  | (1) |

where w\_accj is the weigth of the accelerogram, assumed to be the same for all accelerograms (w\_accj=1/7), w\_modk is the weigth of the P3D model (w\_modk=0.05 for each of the 10 models based on INGV data and w\_modk=0.5 for the OGS model), while Fijk is the amplification factor Fi associated with the j-th accelerogram and the k-th P3D model. As an example, Figure 2 shows the map of the amplification factors in terms of PGA, computed for the municipality of Cavezzo, considering the 475 years-return period. The largest amplification factors are expected in the northern part of the municipality, in the proximity of the culmination of the Mirandola anticline. Moreover, it is interesting to note that this map clearly reflects the local geological and geomorphological context. Following the approach described above, acceleration response spectra with 5% damping were computed for each of the 2,984 grid points.

|  |  |
| --- | --- |
|  | (2) |

1. **RESULTS**
2. **DISCUSSION AND CONCLUSIONS**

**ACKNOWLEDGMENTS**

This research has been carried out within the framework of the European LIQUEFACT project. The LIQUEFACT project has received funding from the European Union’s Horizon 2020 Research and Innovation Programme under Grant Agreement No. 700748. This support is gratefully acknowledged by the authors.

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**TABLES**

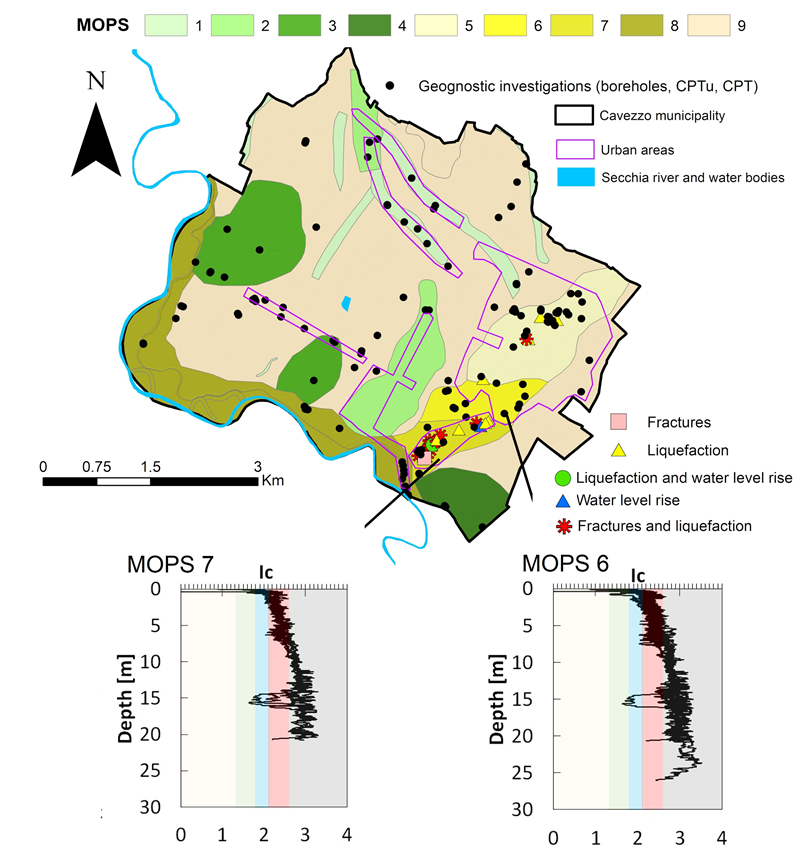
**Table 1** Parameters adopted for the definition of the seismic hazard in Cavezzo, according with the NTC (2008) and NTC (2018).

|  |  |  |  |
| --- | --- | --- | --- |
| **Return period (years)** | **ag (g)** | **F0 (-)** | **Tc\* (s)** |
| 475 | 0.151 | 2.588 | 0.270 |
| 975 | 0.202 | 2.535 | 0.276 |
| 2475 | 0.290 | 2.436 | 0.291 |

**FIGURES**

|  |
| --- |
|  |
| (a) |
|  |
| (b) |

**Figure 1.** Comparison between the map showing the existing data available for the territory of Cavezzo before the LIQUEFACT project started in 2016 (a) and the map showing data acquired during the LIQUEFACT project for improving the ground characterization of Cavezzo territory (b). The manifestations of soil liquefaction occurred in 2012 sequence (black dots) and 1m resolution DEM are also superimposed. Modified from Lai et al. (2019).



**Figure 2** Map of 9 homogenous areas defined for Cavezzo municipality (Meisina et al 2019).



**Figure 3** Map of amplification factor computed for Cavezzo considering the 475-years return period. Top left: PGA; Top right: Housner intensity ratio (0.1s≤T≤0.5s); Bottom left: Housner intensity ratio (0.5s≤T≤1.0s); Bottom right: Housner intensity ratio (0.5s≤T≤1.5s)



**Figure 4** Calibration of shear modulus and damping ratio decaying curves as proposed by Darendeli (2001) using data from laboratory tests performed in December 2017 in Southern area of Cavezzo municipality.