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Brief communication: PERL: a dataset of geotechnical, geophysical, and hydrogeological parameters for earthquake-induced hazards assessment in Terre del Reno (Emilia Romagna, Italy)

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Abstract. In 2012, Italy was struck by a seismic crisis characterized by two main shocks (ML 5.9 and 5.8) and relevant liquefaction events. Terre del Reno (Emilia-Romagna Region) is one of the municipalities that experienced the most extensive liquefaction effects due to its complex geo-stratigraphic and geo-morphological setting. Thus, it was chosen as case study for the PERL project, devoted to defining a new integrated methodology to assess the liquefaction susceptibility in complex stratigraphic conditions through a multi-level approach. About 1800 geotechnical, geophysical and hydrogeological investigations were collected and stored in a publicly available dataset named PERL that is here presented.

1 Introduction

In these last years, an increasing number of source data are publicly disclosed, allowing a wider access to research activities. Key examples are the huge amount of free satellite imagery (i.e., Sentinel, Landsat) provided by the main space agencies and the cutting-edge tools and procedures integrated in widely known and open source EO platforms such as Google Engine. A multitude of algorithms and codes are available for all the fields of knowledge concerning natural hazards, while their application is made easier by the increasing number of open-access inventories of natural phenomena (i.e., Martino et al. 2014; Tanyaş et al., 2022). However, only a few datasets of in-situ investigations and related parameters are publicly disclosed, and this could represent a gap to be filled. As regards to macro-types of investigations (i.e., geological, geophysical, geotechnical, hydrogeological, etc.), some databases are currently available worldwide (i.e., Orgiazzi et al., 2017, Kmoch et al., 2021, Geyin et al., 2021, Minarelli et al., 2022), as well as for the Italian national territory. An example is provided by Vannocci et al. 2022, which includes geotechnical and hydrological soil parameters for shallow landslide modelling.

However, there are only a few examples of freely available products which integrate different macro-typologies of in-situ investigations in a unique database, especially with reference to the Italian territory. In the light of the above, the aim of the authors is to make freely available a dataset of about 1800 geological, geophysical, geotechnical and hydrogeological in-situ investigations and related parameters collected in the Terre del Reno municipality (Emilia – Romagna Region, Italy). The study area is affected by to severe seismic hazards and prone to seismically induced effects, as extensively documented by the 2012 seismic sequence, which was characterized by more than 2000 earthquakes (Facciorusso et al., 2016). Two main shocks were recorded during the crisis: the first one on 20th May with ML 5.9 and epicenter in Finale Emilia (Modena Province), and the second one on 29th May with ML 5.8 and epicenter in Medolla (Modena Province). These events triggered several earthquake-induced effects (Chini et al., 2015, Papathanassiou et al., 2015, Paolella et al. 2022), among which linear and punctual liquefaction effects were the most prominent. Such effects are related to the complex sedimentological and stratigraphic setting of the ares (i.e. Stefani et al., 2018, Tentori et al., 2022), characterized by multiple and alternate sandy and silty-sandy deposits hosting local (shallow) and regional (deep) aquifers (Regione Emilia – Romagna, 1998).

When saturated granular deposits are shaken by a seismic excitation, liquefaction may occur depending on the combination of earthquake intensity and soil density. The case study of Terre del Reno was chosen for PERL project considering the susceptibility of subsoil and the seismicity of the area pursuing two main objectives: i) to define a new integrated methodology to assess the liquefaction susceptibility in complex stratigraphic settings through a multi-level approach; ii) to perform the seismic microzonation of the municipality for land and civil protection planning purposes. The PERL project allowed the collection and analysis of the above mentioned in-situ investigations, and the elaboration of thousands related parameters. The availability of such a dataset of surveys, catalogued and processed according to shared standards, makes Terre del Reno one of the best-characterized municipalities in Italy in terms of seismic hazard and earthquake-induced effects. This proposed database represents a powerful resource for the scientific community, for those who cannot set-up and manage a living laboratory or directly perform on-site investigations. For these reasons, authors provide a complete access to the dataset through the supplementary materials.

2 Materials and methods

The PERL dataset was obtained by merging three databases provided by different institutions. Moreover, additional 17 geotechnical investigations were specifically performed in the framework of the PERL project.

The three existing databases are:

- MUDE database (Modello Unico Digitale per l'Edilizia – Unique Digital Model for Building)

The MUDE database is composed by 384 records including punctual and linear in-situ investigations. These were extracted from a series of technical reports produced to design the reconstruction of the buildings collapsed during the 2012 seismic crisis. Since the digital formats of these investigations were originally not available, geo-localization, key information and measured parameters were obtained from the digital scans of technical and geological reports.

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- RER database (Regione Emilia-Romagna - Emilia-Romagna Region database)

The RER database is composed by 906 geo-localized, punctual records, associated with a set of keys information (typology, date, coordinates, and maximum depth) and a scan of the investigation sheet. Parameter were extracted from investigations sheets as the are not available in a digital format. This database is available at https://servizimoka.regione.emilia-romagna.it/mokaApp/apps/geg/index.html (last access: 12/09/2022).

- SM database (Seismic Microzonation Studies)

The SM database is composed by 1284 records including punctual as well as linear in-situ investigations. These investigations are geo-localized and organized in a standardized structure according to Commissione tecnica per la microzonazione sismica (2015). The key information (typology, date, coordinates, etc.) of each investigation are stored in a dedicated table, while all the measued parameters are reported in chained tables. This database is available at https://www.webms.it/ (last access: 12/09/2022).

The first problem faced to merge these three databases was the presence of duplicate information. To avoid duplicates, a methodology to discern and verify the uniqueness of an investigation was elaborated.

This methodology is based on the implementation of a series of multiple, progressive True/ False (TF) controls applied to various control parameters (CP) relative to all the investigations included in the pertinence area. This last was defined as a circle with a radius equal to 200 m centered in correspondence of the considered investigation. The progressively considered CP (Fig. 1) are: CP1) absence of another investigation within the area of pertinence; CP2) un-matching of the investigation typology; CP3) un-matching of the date of survey; CP4) matching of depth reached by the investigation. Each CPm (m=1,2,3,4) is checked in a dedicated TF test (TFn with n=1,2,3,4). Starting from TF1, an investigation that verifies CP1 is moved to TF2 for CP2 verification up to TF4. Each time that a CPm in a TFn is not verified, the investigation is defined as “unique”. If an investigation verifies all the control parameters, it is defined as “redundant” and removed from the database. The application of this methodology allowed to identify and remove 32% of the investigations, obtaining a final dataset composed of 1805 unique investigations (Fig. 2).

3 Data description

Finally, PERL dataset is composed by two shapefiles to be implemented into a GIS system and an associated geodatabase. The two shapefiles are named *ind_pc* and *ind_ln* , corresponding to punctual and linear investigations, respectively. The associated attribute tables contain the main information of each investigation:

- *ID:* unique identification number of each investigation ;
- *Long*: longitude (EPSG:32633) ;
- *Lat:* latitude (EPSG: 32633) ;

The complete set of investigations and the related measured parameters are reported in an excel file following this structure:

- *ID:* unique identification number of each investigation
- *Type_par:* typology of parameters (see ‘list of parameters’ for legend)

- *Value:* value of the parameters
- *Depth_top:* top of layer depth (m) to which the parameter refers.
- *Depth_bottom:* bottom of layer depth (m) to which the parameter refers.

PERL dataset includes 1805 records corresponding to as many investigations, and guarantees an average density of 35 punctual and/or linear measurements per square kilometre of Terre del Reno municipality (about 51 km^2). Focusing on investigations typologies (see the list of typologies and codes), the dataset consists of 71% of penetrometer tests (CPT, CPTU, CPTE, SCPT, SPT, DN), 16% of boreholes and trenches (S, T, SP, SC, SD), 12% of punctual and linear geophysical investigations (CH, DH, HVSR, MASW, ESAC_SPAC), 1% of laboratory and hydrogeological tests (CR, CI, CD, SM, ED, TD, LF) (Fig. 3). Penetrometric tests, geognostic boreholes, trenches, and borehole geophysical tests are characterized by a depth of investigation ranging from few meters to more than 100 m (maximum depth: 265m). About the 90% of them, reach a maximum depth of investigation equal to 35m. Thus, the most represented depth classes are 30-35m and 10-15m with 330 (21%) and 310 (20%), respectively. As regards to penetrometric tests, in particular, they are characterized by depths ranging between 5 and 50m, with a maximum in 30-35m class. On the contrary, boreholes and trenches cover the entire spectrum of depth classes of the dataset. However, it is worth noticing that about 60 boreholes and trenches reach a depth higher than 55m, which is the most represented classes together with the 10-15m class. Penetrometer tests, boreholes, trenches, and geophysical tests are characterized by investigation depths ranging from few to some hundred meters with a maximum of 265m. About the 90% of them, reach a maximum depth of investigation equal to 35m. Most investigation ae carried out up to a depth of 30-35m and 10-15m (330 (21%) and 310 (20%) being respectively contained in each class). As regards to penetrometer tests, in particular, they are characterized by depths ranging between 5 and 50m, with a maximum in 30-35m class. On the contrary, boreholes and trenches cover the whole spectrum of depth classes of the dataset. However, it is worth noticing that about 60 boreholes and trenches reach a depth higher than 55m, which is the most represented class together with the 10-15m class.

3 Conclusions

Within the PERL project, a considerable number of investigations were collected in the Terre del Reno municipality (Emilia Romagna Region in the north of Italy), an area exposed to severe seismic hazards and prone to seismically induced effects due to its complex geological setting. In fact, it is one of the municipalities that experienced the most extensive liquefaction effects during the 2012 Emilia Romagna seismic crisis.

Here it is presented and shared the PERL dataset, including 1805 punctual and linear *in-situ* investigations concerning geological, geotechnical, geophysical and hydrogeological data to which it is possible to freely access. Specifically, it is composed of 71% of penetrometer tests, 16% of boreholes and trenches, 12% of geophysical investigations and 1% of laboratory and hydrogeological tests.

This dataset represents a resource for the scientific community, and in particular for those interested in testing and validating new methodologies.

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4 Acknowledgements

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Author contribution

CV, GC and FS conceptualized the methodology. CV, GC, AB, MCC, SF, CF, IG, SG, LP, MS, PS, RS and DT curated the data. GC implemented the algorithm. LM, GM and MM conceptualized and administrated the project. CV wrote the original draft of the paper. CV, GC, AB, MCC, SF, CF, IG, SG, MM, LP, MS, PS, RS, FS, DT, LM, GM and MM reviewed and edited the paper.

Competing interests

The authors declare that they have no known competing interest.

Appendix A : List of investigation typologies and codes

- *CH:* Cross - Hole test
- *CPT:* Cone Penetration Test
- *CPTE:* Electrical Cone Penetration Test
- *CPTU:* Piezocone Penetration Test
- *CR:* Resonant Column Test
- *DH:* Down-Hole test
- *DMT:* DilatoMetric Test
- *DN:* Dynamic Cone Penetration Test
- *ESAC_SPAC:* seismic array elaborated by ESAC/SPAC methods
- *HVSR:* ambient noise measurements elaborated by HVSR technique
- *LF:* LeFranc test
- *MASW:* Multichannel Analysis of Surface Waves
- *PA:* borehole (water well)
- *S:* non-destructive borehole
- *SC:* borehole with collection of samples
- *SCPT:* Seismic Cone Penetration Testing
- *SD:* borehole

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- *SDMT:* Seismic Dilatometer Marchetti Test
- *SM:* laboratory test on soil sample
- *SP:* piezometer
- *SPT:* Standard Penetration Test
- *T:* trench
- *TD:* shear strength test

Appendix B : List of parameters and codes

- *AR:* clay classification obtained from laboratory test (%)
- *C:* effective cohesion (MPa)
- *CAM:* number of sample (-)
- *CU:* undrained cohesion (MPa)
- *E1:* index of voids (-)
- *F1:* effective soil friction angle (˚)
- *FR:* resonance frequency (Hz)
- *FS:* skin friction (MPa)
- *G:* shear modulus (MPa)
- *GH:* gravel classification obtained from laboratory test (%)
- *IP:* plasticity index (-)
- *K:* classification obtained from laboratory test (m/s)
- *L:* layer lithology (-)
- *LID:* lithology of the hydrolayer (-)
- *LM:* silt classification obtained from laboratory test (%)
- *PT:* number of SPT blows (-)
- *PTM:* number of DN blows (-)
- *PV: w*eight of the unit of volume (kN/m^3)
- *QC:* tip resistance (MPa)
- *SA:* sand classification obtained from laboratory test (%)
- *SG:* water table level (m)
- *U:* hydrostatic pressure (MPa)
- *VP:* compressional waves velocity (m/s)
- *VS:* shear-waves velocity (m/s)
- *W:* water content (%)

Appendix C : List of lithologies (L) and codes

- *CH*: inorganic clays with high plasticity
- *CL:* inorganic clays with low- medium plasticity, gravelly or sandy, silty clays
- *GP:* clean gravel poorly graded, mixture of gravel and sand
- *MH:* inorganic silts, fine sands, micaceous or diatomitic silts
- *ML*: inorganic silts, silty or clayey fine sands, silts clayey sands with low plasticity
- *OH:* organic clays of medium-high plasticity, organic silts
- *OL:* organic silt, silty clays with low plasticity
- *PT:* peats and peaty soils

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- *RI:* anthropogenic filling
- *SC:* clayey sands, mixture of sand and clay
- *SM:* silty sands, mixture of sand and silt
- *SP:* sands poorly graded
- *SW:* sands well graded, gravelly sands

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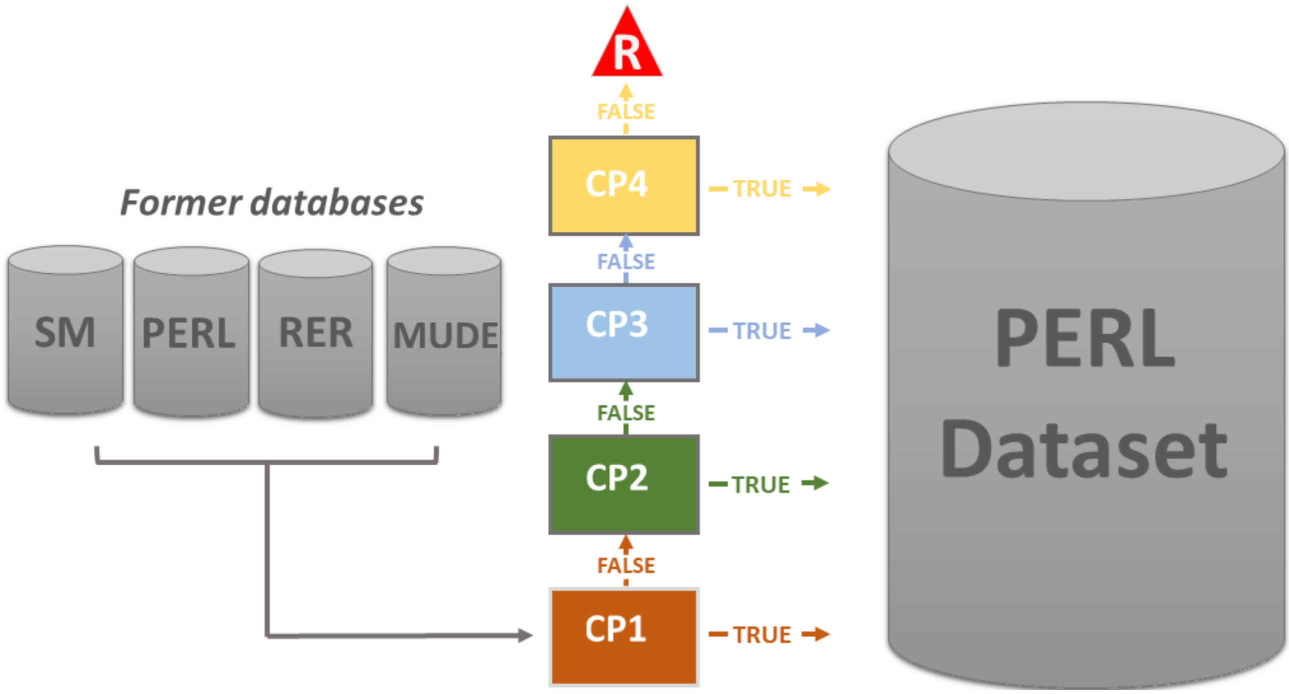

255 **Figure 1: Synthetic workflow of the applied method to merge MUDE, RER, SM database and PER new realization investigations into PERL dataset.**

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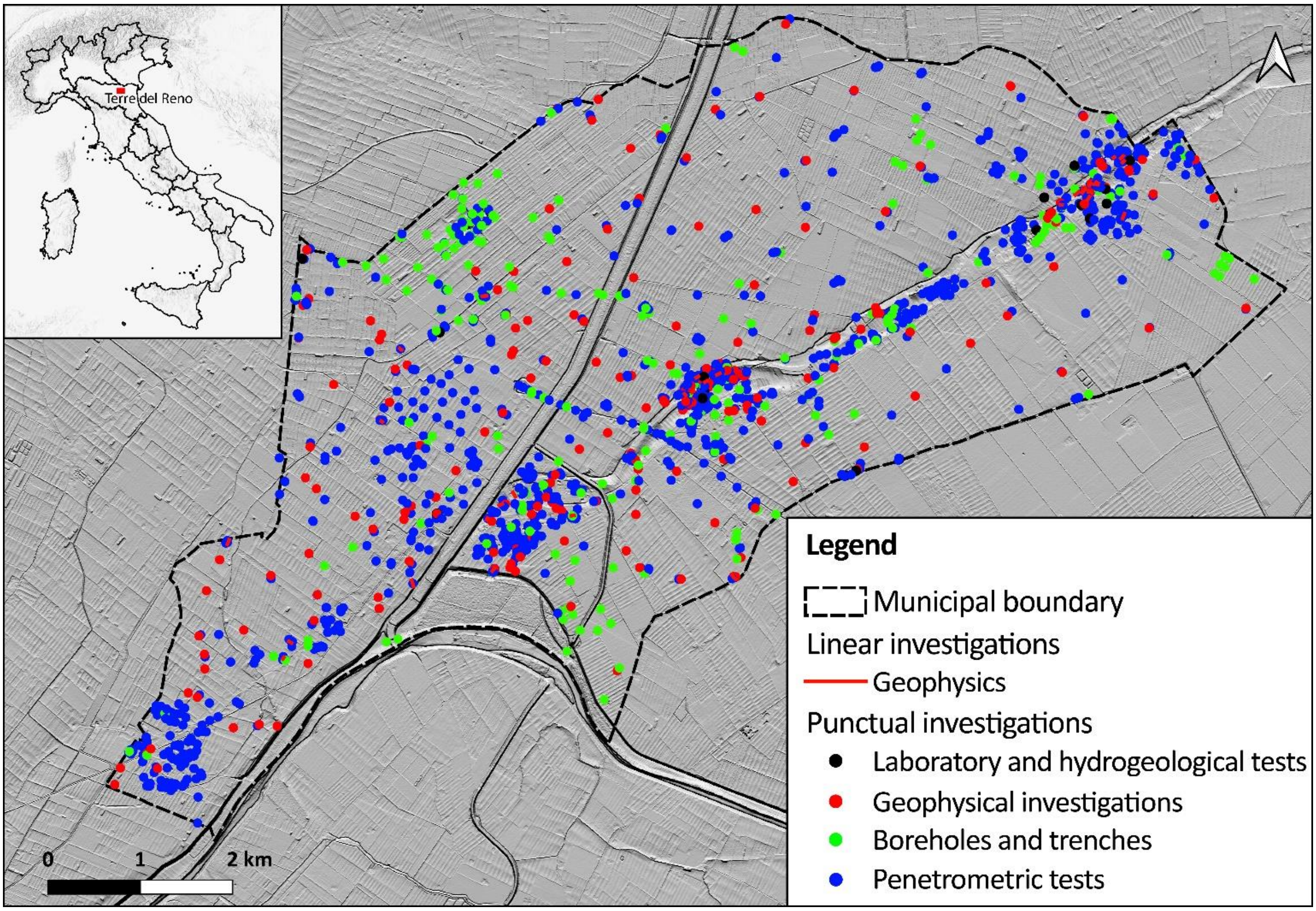

260 **Figure 2: Spatial distribution of the in-situ investigations composing the PERL dataset. The Digital Elevation Model (DEM) was retrieved from Regione Emilia Romagna (2015)**

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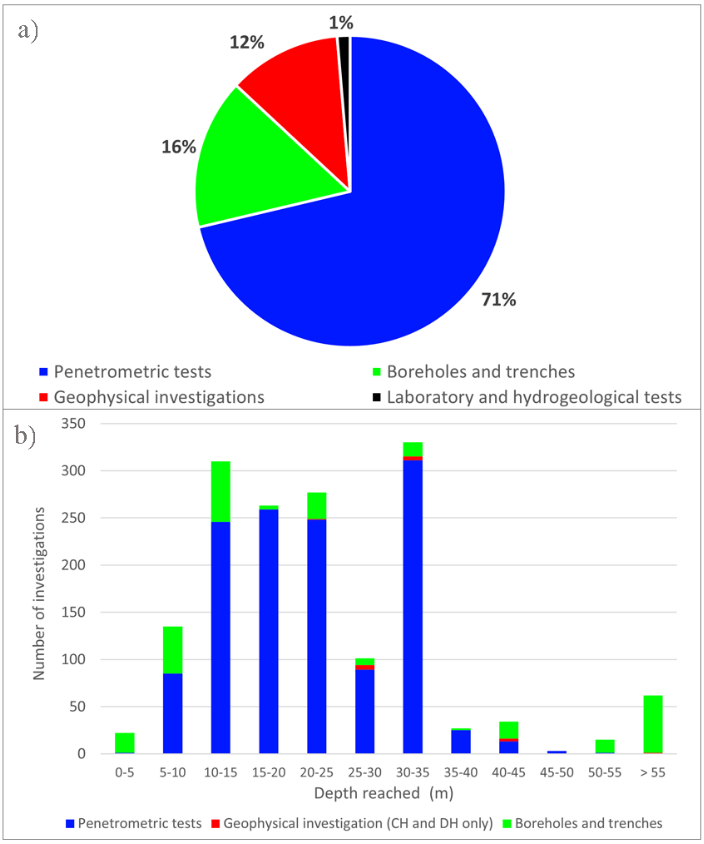

Figure 3: PERL dataset characteristics: a) classes of in-situ investigations; b) depth reached by penetrometer tests, geophysical investigations (CH and DH), boreholes and trenches.