Local seismic effects forecast supporting risk mitigation in the Ferrara area.

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Introduction

The history of Ferrara has been marked by many significant earthquakes, documented since 1117 (Guidoboni 1984; Locati et al. 2016; Guidoboni et al. 2018 and Guidoboni et al. 2019). The worst documented damage occurred during the 1570 earthquakes. The seismic activity was generated by reverse and, sometimes, strike-slip faults of the Apennines chain front, buried under thick Plio-Pleistocene foredeep deposits. The damage to the anthropic structures was modulated by local seismic effects, reflecting the complex stratigraphical, geophysical, and geotechnical features of the area. The subsurface architecture induced seismic wave amplification and, at sites, coseismic liquefaction of water-saturated granular sediments, as occurred in the urban area of Ferrara during the 1570 earthquakes (Guidoboni and Valensise 2023), and in adjacent areas in the year 2012 (Minarelli et al. 2022). For developing the research, over 4,000 pre-existing geophysical, stratigraphical, and geotechnical investigations were collected into a homogeneous database, and analyzed together with the new investigations we carried out, such as seismic noise measurements, seismic piezocone, and seismic dilatometer tests. Numerical modeling for the seismic response analysis was also performed.

Geology and Stratigraphy

The distribution and properties of the outcropping fluvial sediments were reconstructed through remote sensing, field investigation, and geotechnical testing. The Po channel sands (Fig. 1a), mainly Medieval in age, form elongated bodies in northern areas, whereas, in southern zones, the Reno channel silty sand and silts accumulated during the XVII century. In south-eastern areas, Roman Times Po and Reno channel bodies are sub-outcropping. The fluvial channel deposits are flanked by finely granular natural levee belts. Most of the study area consists of mainly cohesive, argillaceous sediments, accumulated into interfluvial settings (Fig. 1a). The conceptual correlation of the abundant cone penetrations tests and stratigraphic cores generated a subsurface geological model, developed throughout the wide Ferrara Municipality area, integrated, in the urban and peri-urban zone, by a lithostratigraphy 3D model, produced by automated interpolation techniques. To generate the model, synthetic lithological columns were derived from the comparison of the tip resistance and lateral friction values, interpreted according to the Roberston classes (Robertson 1990, 2009). The synthetic lithological logs and the actual stratigraphic cores were then laterally correlated, using trilinear and tricubic interpolation algorithms, to generate continuous 3D subsoil models of the first 40 m of subsurface (Fig. 1b, c).

In northern areas, the lower part of the study stratigraphic interval consists of Wuermian synglacial sands, sedimented by the river Po, which southward give way to finer grained units, mainly accumulated by Apennines rivers (Fig. 1c). Throughout the area, the synglacial units are topped by a terraced discordance surface, followed by syn-transgressive continental silty deposits, and by Holocene highstand fine grained sediments, associated with Po River channel sands and, in southern areas, with finer grained sediments of Apennines provenance. Based on the two geological models, 21 stratigraphic microzones (MOPS), homogeneous from a seismic response point of view, have been defined in the first 30 m of subsurface. The petrophysical properties of the microzones control the near surface seismic wave amplification and liquefaction hazard.

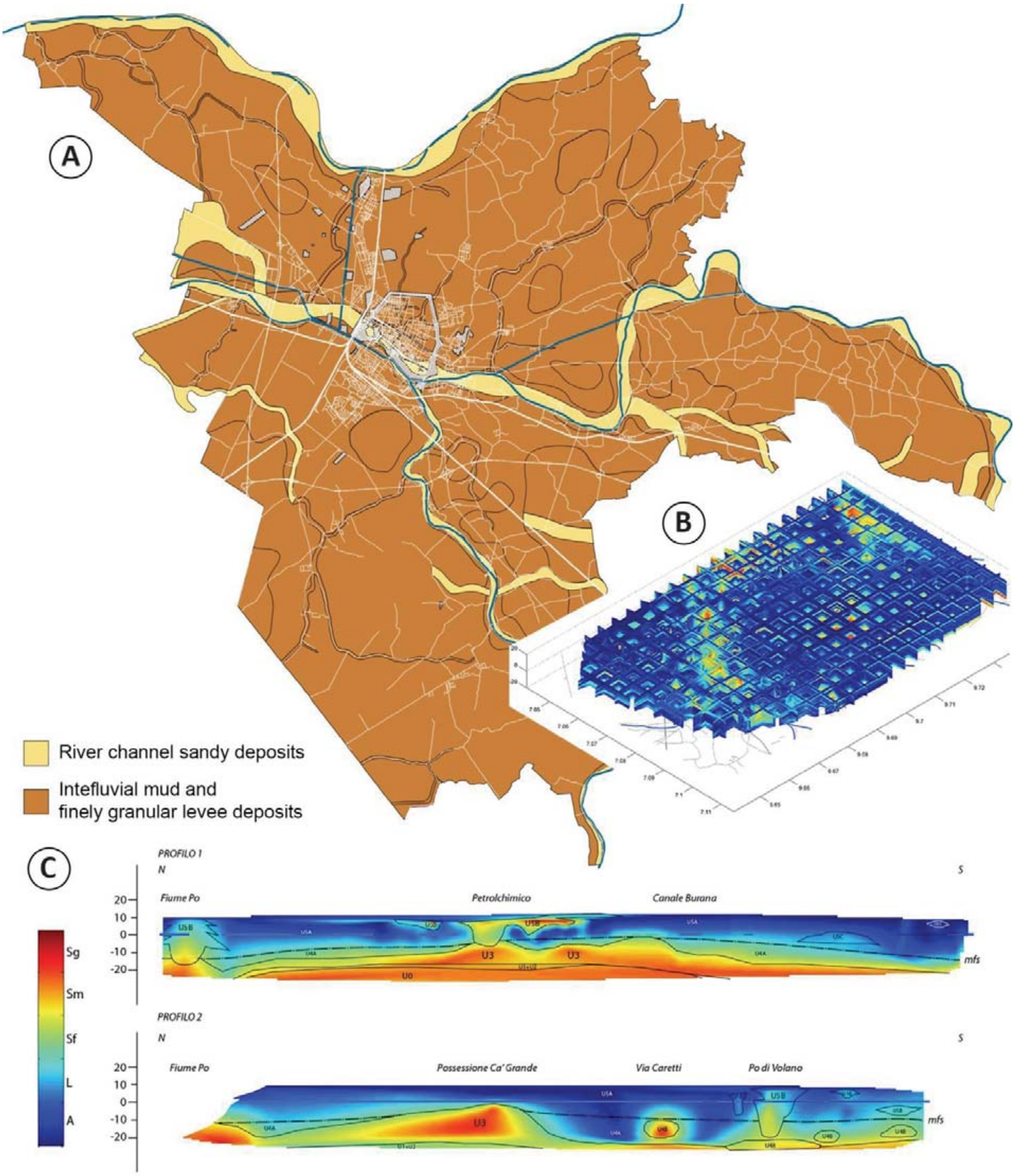

Fig. 1 – (A) Engineering-geological map of the Ferrara municipality area, the yellow ribbons depict Po and Reno channel sand bodies; (B) enclosure diagram extracted from the the 3D model of the first 40 m of the urban area subsurface, derived from the automated tricubic interpolation of more than 1000 subsurface logs; (C) N-S sections extracted from the same model, sand lithologies are depicted in red, cohesive muds in blue, late Pleistocene synglacial sands are covered by Holocene lower alluvial plain deposits.

Seismic amplification and local response

The spectral selective amplification of seismic waves shows rapid spatial variations, even within the comparatively small urban area of Ferrara, due to the complex geological architecture. The seismic bedrock, defined by rocks with S-waves speed exceeding 800 m/s, is everywhere covered by thick unlithified late Quaternary units. The bedrock rises in the anticline area (Casaglia) to its minimum depth, at about 100 m, and largely sinks towards the subsiding southern syncline zone, where normally exceeds 300 m in depth. The deepening of the seismic substratum shifts the amplification peaks toward lower frequencies. To evaluate the forecasted acceleration at the surface, seismic microzonation studies require to input the seismic intensity, estimated on the bedrock top, with a 10% occurrence probability, over a 50-year time interval, which is provided by the Italian seismic hazard map (Meletti et al. 2006; Stucchi et al, 2011).

To evaluate the seismic motion amplification induced by the unlithified stratigraphic units overlaying the bedrocks, the amplification factor abacuses proposed by the Emilia-Romagna Region for alluvial plain areas were initially used. Two separate abacuses were applied. The "Pianura 2" abacus was used for the areas where the bedrock top is less than 150 m deep, while for the greater portion of the municipal area, with bedrock exceeding 300 m in depth, the "Pianura 3" one was applied. The amplification factors predicted by the abacuses were compared with those derived from our detailed local seismic response analyses (Fig. 2). The good match of the results supports the use of the abacuses approximation. The response analyses was performed in the anticline area and in different portions of the historic center, developed on fluvial sands or on interfluvial muds (Fig. 1, 2). We then forecasted the areal distribution of damage, according to the "synthetic damage constrained parameter" (HSM, Naso 2019), related to the forecasted site shaking, expressed in cm/s^2. The HSM values in turn support the damage estimation. Medium to severe damage is expected for the largest portion of the Municipality of Ferrara, including the whole urban area.

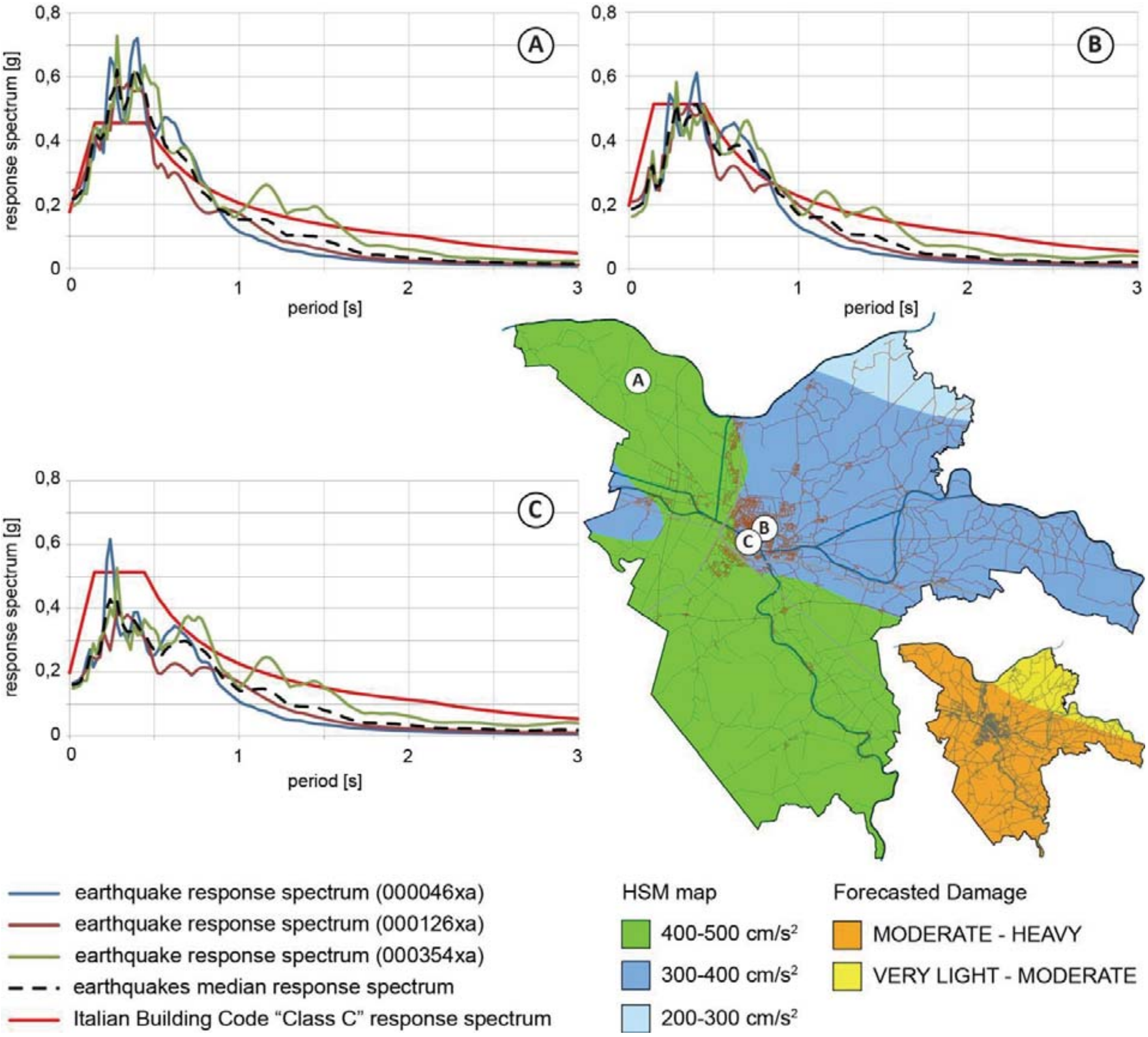

Fig. 2 – Distribution of the damage parameter expressed as acceleration in cm/s^2 and of the expected damage estimation: Medium-Severe damage is forecast for the urban area. Green areas indicate higher acceleration values than in the blue ones, orange zones more severe damage than the yellow ones. The three graphs illustrate the different spectrally selective amplification responses to the seismic acceleration, in the structural high area (A), and in the urban center, respectively on the Po channel sand body (B) and on interfluvial mud areas (C).

Coseismic liquefaction hazard

To evaluate the local liquefaction hazard, more than 400 punctual analyses were performed, processing cone penetration data through the Boulanger and Idriss (2014) "simplified method". Liquefaction hazard maps were then generated through the geology-based surface interpolation of the punctual estimations. The Liquefaction Potential Indexes LPI (Iwazaki et al., 1982) were subdivided into classes (Sonmez, 2003), to distinguish areas of low ($0 < LPI \leq 2$), moderate ($2 < LPI \leq 5$), and high ($5 < LPI \leq 15$) hazard. A high liquefaction susceptibility is mainly confined to the channel sand bodies deposited by the Po. The sites where the 1570 liquefaction is documented show medium to high hazard index values, validating the estimation procedure, as in the southern portion of the Medieval town and at Torre Fossa (Fig. 3). The forecasted effects of the liquefaction will be largely increased by the presence of slopes and artificial embankments, which can trigger gravitational lateral spreading. The remaining portions of the study area are generally spared from the liquefaction hazard but are subject to seismic settlements and significant seismic amplification factors.

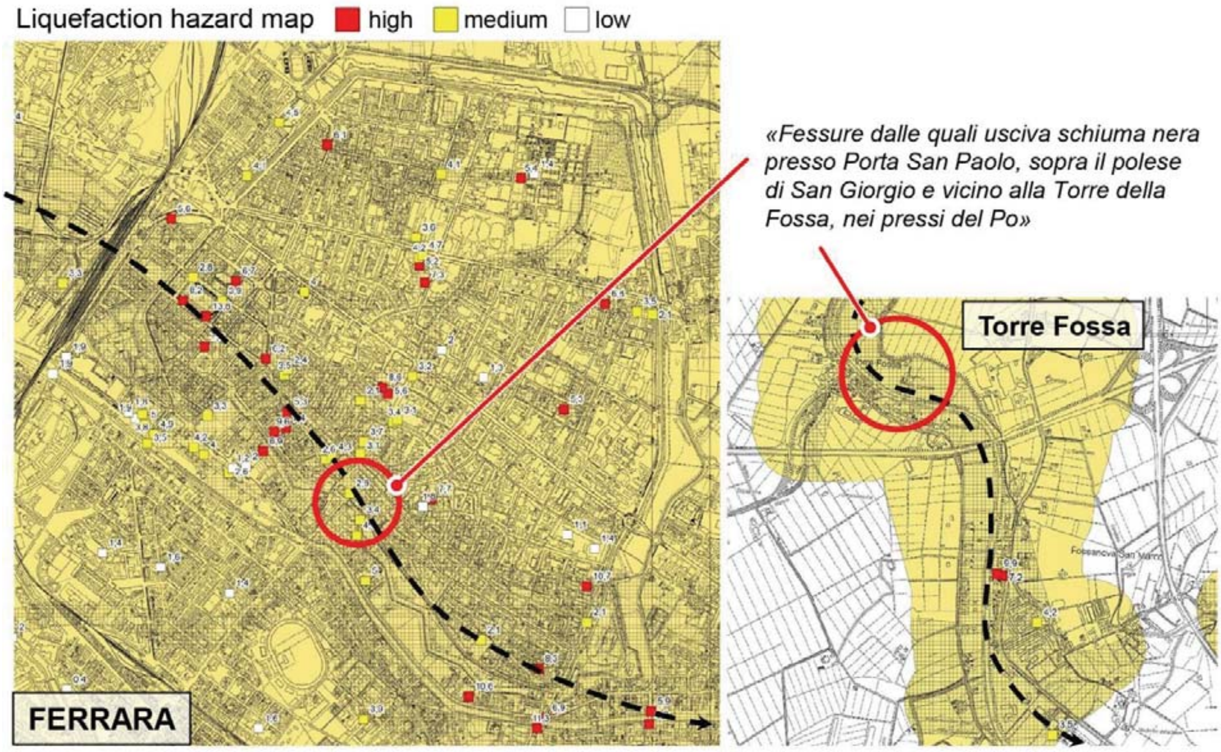

Fig. 3 – Liquefaction hazard map, red squares indicate points of high liquefaction hazard, the Po channel sands always show high or intermediate values. The circles indicate areas where liquefaction was reported in November 1570, near Castel Nuovo – Porta San Paolo and Torre Fossa. The quotation is from a manuscript describing the November 1570 earthquake (Guidoboni 1984).

Conclusions

Interdisciplinary research, integrating geological, geotechnical, geophysical, and computational geostatistics techniques, supported an accurate microzonation of the seismic hazard of the study area. Large spectral selective amplification was demonstrated, showing strong spatial variation gradients. Medium-severe damage is forecasted throughout much of the municipality area. Moderate to high liquefaction hazard characterizes the late Holocene Po channel sand bodies, on which the southern portion of the Medieval town developed. The outskirt areas built on both Po and Reno granular sediments are also subject to significant liquefaction hazard. The impact of the coseismic liquefaction will be multiplied by the lateral spreading of embankments and ridges. The remaining portions of the municipality are developed on cohesive interfluvial sediments and are therefore spared from liquefaction hazard, but still subject to significant seismic wave amplification. The research was aimed at supporting the development of appropriate urban planning and politics. The spatial distribution of the areas subject to liquefaction must be considered in the design of anti-seismic buildings and architecture restoration procedures. The increased knowledge of the risk affecting the town should prompt a massive effort to mitigate the expected damage, by improving the seismic response of both ancient and modern buildings, especially for the many of them built before the Italian seismic code implementation. Improved public awareness should spur action to mitigate the serious risks to which both buildings and people’s lives are now subject.

References

Boulanger R. W., Idriss I. M.; 2014: CPT and SPT based liquefaction triggering procedures. Report No. UCD/CGM-14/01, Center for Geotechnical Modeling, Department of Civil and Environmental Engineering, University of California, Davis, CA, 134 pp.

Guidoboni E.; 1984: Riti di calamità: terremoti a Ferrara nel 1570-74, Quaderni storici 55/ a. XIX, n. 1.

Guidoboni E., Valensise G.; 2023: *L’Italia dei Terremoti, l’Azzardo Sismico delle Città*. Vol. 2, Centro-Nord. Fondazione CNI, 668 pp.

Guidoboni E., Ferrari G., Mariotti D., Comastri A., Tarabusi G., Sgattoni G., Valensise G.; 2018: *CFTI5Med, Catalogo dei Forti Terremoti in Italia (461 a.C.-1997) e nell’area Mediterranea (760 a.C.-1500).* Istituto Nazionale di Geofisica e Vulcanologia (INGV). Guidoboni E., Ferrari G., Tarabusi G., Sgattoni G., Comastri A., Mariotti D., Ciuccarelli C., Bianchi M.G., Valensise G.; 2019: *CFTI5Med, the new release of the catalogue of strong earthquakes in Italy and in the Mediterranean area.* Scientific Data 6, Article Number: 80 (2019).

Iwasaki T., Arakawa T., Tokida K.; 1982: Simplified procedures for assessing soil liquefaction during earthquakes. Proceedings of the Conference on Soil Dynam, p. 49-58.

Locati M., Camassi R., Rovida A., Ercolani E., Bernardini F., Castelli V., Caracciolo C.H., Tertulliani A., Rossi A., Azzaro R., D’amico S., Conte S., Rochetti E.; 2016: *DBMI15, the 2015 version of the Italian Macroseismic Database*. Istituto Nazionale di Geofisica e Vulcanologia.

Meletti C., Montaldo V., Stucchi M., Martinelli F.; 2006: *Database della pericolosità sismica MPS04*. Istituto Nazionale di Geofisica e Vulcanologia (INGV).

Minarelli L, Amoroso S., Civico R., De Martini P.M., Lugli S., Martelli L., Molisso F., Rollins K.M., Salocchi A., Stefani M., Cultrera G., Milana G., Fontanta D.; 2022: *Liquefied sites of the 2012 Emilia earthquake: a comprehensive database of the geological and geotechnical features (Quaternary alluvial Po plain, Italy)*. BULLETIN OF EARTHQUAKE ENGINEERING, v. 20, p. 3659-3697.

Naso G., Martelli L., Baglione M., Bramerini F., Castenetto S., D’Intinosante V., Ercolessi G.; 2019: *Maps for land management: from geology to seismic hazard*. Boll. Geof. Teor. App. Vol. 60, n.2, June 2019, p. 277-294.

Robertson P.K.; 1990: *Soil classification using the cone penetration test*. Canadian Geotechnical Journal, 27(1), p. 151-158.

Robertson P.K.; 2009: *Interpretation of cone penetration tests — a unified approach*. Can. 34 650 Geotech. J. 46, p. 1337–1355.

Stucchi M., Meletti C., Montaldo V., Crowley H., Calvi G.M., Boschi E.; 2011: *Seismic Hazard Assessment (2003-2009) for the Italian Building Code.* Bull. Seismol. Soc. Am. 101(4), p. 1885-1911.

Sonmez H.; 2003: Modification to the liquefaction potential index and liquefaction susceptibility mapping for a liquefaction-prone area (Inegol-Turkey). Environ. Geology 44(7), p. 862-871.

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