Seismic Stability Analyses of the Po River Banks

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Abstract
The Po River is the major Italian watercourse. Over half its length is controlled with embankments as protection measures against heavy floodings. Recently, the Italian Government has funded a project for the evaluation of the seismic stability of about 90 km of embankments of the Po River. The project mainly aims at the seismic stability analyses of the river banks, with assessment of local site response and evaluation of the liquefaction potential. Hundreds of geotechnical investigations within the study area were performed and the water level variations in the embankment and subsoil were investigated using piezometers. This paper describes the methodology and the main results of the analyses. The safety of 43 significant sections in static and seismic conditions was investigated using limit equilibrium analyses. Dynamic effects in the seismic condition were considered using the pseudostatic method. Local seismic hazard and effects of site conditions on the ground motion are taken into account in the definition of the expected seismic action. Eventually, the analysis results are summarized in a static and seismic stability map of the investigated area, a useful tool for the local Authority in the prevention and mitigation.

Keywords
River banks • Stability analysis • In situ tests • Seismic hazard • Stability maps

150.1 Introduction

The stability of embankments is a crucial issue for public safety and for the consequences that a possible failure event may have on the territory and its economy. Although the seismic hazard of the Po valley is not very high, the related flood risk is extremely significant due to the vulnerability of the levees and to the relevant exposure of the territory. The Italian Government has funded an extensive project for the evaluation of the seismic stability of about 90 km of embankments of the Po River in the municipalities with the highest seismic hazard (between the municipalities of Boretto, in Reggio Emilia Province, and Ro, in Ferrara Province) (Fig. 150.1a). All activities were promoted and coordinated by the relevant Po river Authority (Autorità di Bacino of the Po River—AdBPO).

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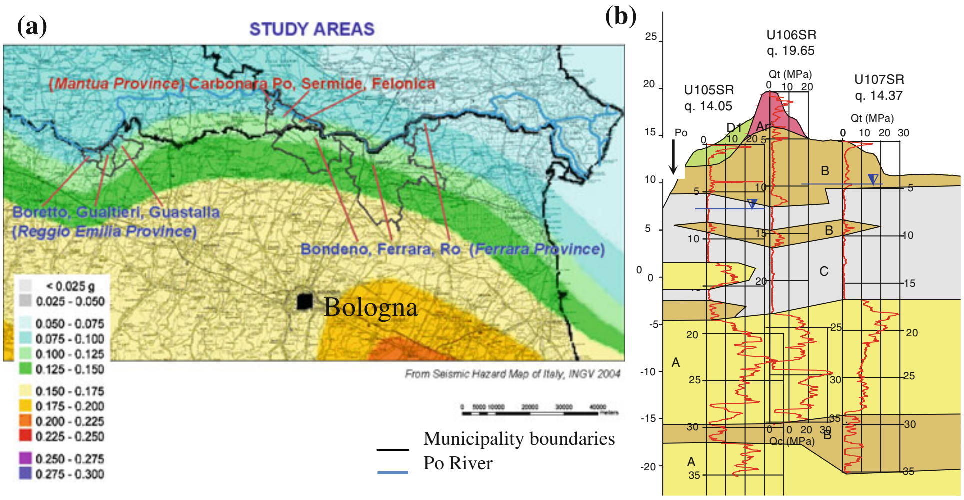

Fig. 150.1 **a** Location of the study area and **b** typical geological cross-section of the Po river embankments (Martelli et al. 2011)

150.2 Geological Model and Groundwater Monitoring

Hundred of in situ and laboratory tests were carried out within the project. A total of 107 geological profiles (99 transversal and 8 longitudinal) were thus drawn regularly distributed along the 90 km of the investigated embankments. A typical cross section of the embankment with the relevant geological model is shown in Fig. 150.1b. The stratigraphy of the embankment-subsoil system includes: the embankment (Unit A_r^*) characterized by landfill organized in alternating layers, various thickness, of sands, silty sands, sandy silts and clayey silts, with sporadic presence of brick fragments. The subsoil of the embankment frequently consists of a layer of natural levee environment characterized by sandy silts alternating to fine and very fine silty sands including centimetric or decimetric more sandy and clayey-silty levels (Unit B). In other cases the subsoil consists of clayey and silty deposits of floodplain environment (Unit C), with centimetric and decimetric levels of peat and blackish frustules of organic material or fine to very fine silty sands and sandy silts. In the upper part of Unit B and C, a shallow (not more than ten meters) phreatic aquifer is located. River side, the accumulation of floodplain deposits (Unit D) was favoured by the presence of the embankments. Two main facies can be identified in this Unit: a mainly fine (D1) and a sandy facies (Unit D2). The sequence continues downward with prevailing sands attributable to fluvial channel environment (Unit A). An important aquifer, generally confined, is there located; however, near the levees and the floodplain area, the two aquifers (phreatic and confined) sometimes merge. In order to verify the hydraulic conditions in the embankment subsoil, the unconfined and confined aquifers have been monitored with piezometers since February 2011.

Recorded data (Fig. 150.2) show that the river and the confined aquifer are synchronized and generally drain the unconfined aquifer. Most of the time the confined aquifer has a piezometric level about 1–2 m lower than the unconfined aquifer, but during significant floods this condition is reversed. In addition, data collected at present suggest that the groundwater level lies below the embankment body also during the main flood events.

150.3 Local Site Response and Evaluation of the Liquefaction Potential

The definition of the expected input motion was performed by considering the seismic hazard at four sites considered as representative to as many macro-areas: Guastalla, Sermide, Ferrara and Bondeno respectively. Two different probabilistic approaches for seismic hazard estimates were considered on purpose: the first one is the standard Cornell-McGuire approach in the implementation adopted for the compilation of the National Seismic Hazard Map of Italy (Stucchi et al. 2011) and the second one is the probabilistic approach developed to evaluate seismic hazard from macroseismic information (Albarello and Mucciarelli 2002). Considering the acceleration target spectra, 6 measured accelerograms (spectrum-compatible) have been selected and considered as possible input motions for each macro-area. The analyses of the local seismic response were performed through the following steps. The first step included the analyses of the geologic, geophysical and geotechnical data for each macro-area. The second step included the comparison be-tween the results of the different geophysical investigations (DH, CH, MASW, REMI, SCPTU) to obtain the values of the shear waves velocities (V_s) for each geologic unit representative of the stratigraphic sequences and the individuation of a number

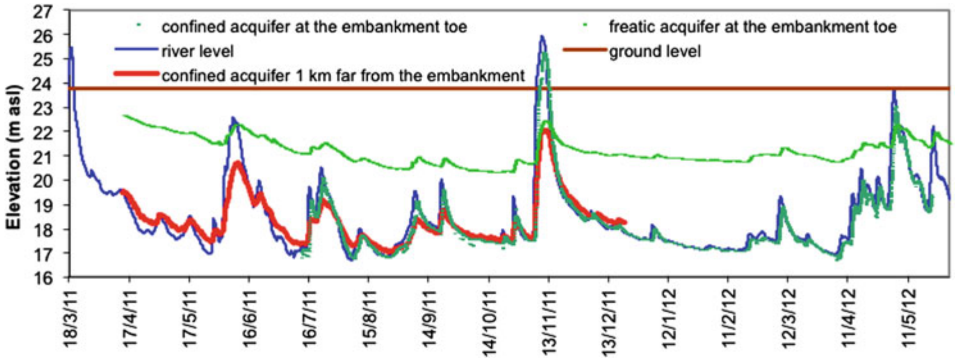

Fig. 150.2 Typical trend of the river level (*blue line*), compared with the hydraulic heads measured in the confined and unconfined aquifers at the embankment toe (*green lines*), and in the confined aquifer 1 km far from the embankment (*red line*)

of typical seismo-stratigraphic sequences. The third step concerned the choice of the static and dynamic parameters for each geologic unit, particularly the unit weight (γ_n), the initial damping ratio (D_0), the variation curves of the shear modulus (G) and damping ratio (D) with the shear strain (γ), finalized to the numerical analyses. The numerical analyses, for each typical seismo-stratigraphic sequence, were performed using a one-dimensional (1D) numerical code. The 6 accelerograms assigned for each macro-area were applied to each seismo-stratigraphic sequence and the results were given in term of average amplification factors and average acceleration response spectra at 5 % of the critical damping. The evaluation of the liquefaction hazard was performed through the following steps: analysis of the standard seismic hazard data finalized to the individuation of the hazard parameters as the expected maximum horizontal acceleration and the moment magnitude (a_g and M_w) of the studied area; analysis of the geologic, geo-physical and geotechnical data finalized to the individuation of the parameters re-lated to each analysed column; preliminary susceptibility analyses to liquefaction, devoted to the identification of the existence of the triggering characters of the phenomena in the whole studied area; liquefaction analyses by means of simplified methods, in all the analysed columns and identification of the relative liquefaction index IL; comparison of all the obtained results in term of IL values and individuation of the areas characterized by high severity of possible liquefaction ($IL > 5$) and subsequent evaluation of the consequent permanent settlements in the deposits characterized by the occurrence of liquefaction phenomena.

150.4 Geotechnical Model

Stratigraphic soil profiling as well as geotechnical characterization of the riverbank sediments and the surrounding subsoil mainly relied on in situ tests, with special reference to piezocone data. In the adopted procedure, detailed stratigraphic profiles were derived by applying the well-known and newly revised classification framework developed by Robertson (2009), based on the stress normalized CPTU measurements. Accordingly with the geological model, the same typical soil units were identified and the geotechnical property variability is concisely described by the coefficient of variation (Phoon and Kulhawy 1999). From the interpretation of the large amount of available data, it turns out that unit A is typically characterized by a mean friction angle $\phi'_m = 35° \div 36°$ and a standard deviation SD $\cong$ 2°; unit B by $\phi'_m \cong 32°$ and SD $\cong$ 1°, unit C by $\phi'_m \cong 24°$ and SD $\cong$ 2°. Finally, as regards the sandy-silty mixtures forming the riverbanks (unit A_r^*), typical values of mean friction angle ϕ'_m are 32° with a standard deviation SD $\cong$ 1.5°.

150.5 Static and Seismic Stability Analyses

Among the 99 cross sections of the geological model, 43 were selected to perform numerical stability analyses, following a criterion of representativeness and uniform distribution along the river (Gottardi et al. 2013). Limit equilibrium analyses for assessing the stability of the riverbanks in different hydraulic conditions were performed under both static and seismic conditions. The ordinary and the maximum water levels (peak flow) were considered in static effective stress analyses, with steady seepage flow inside the embankment. A partial rapid drawdown condition was also considered for the upstream slope of the embankments. A drawdown of 4.7 m (average of the recorded data in the 7 days after the peak event) from the maximum level was considered. Seismic analyses were performed by using the pseudostatic method and with reference to an ordinary water level. The design horizontal pseudostatic coefficient (K_h) was calculated as a fraction of the peak ground acceleration obtained from local seismic response in free field at the bottom of the embankment. According to the Italian building code, the reduction coefficient was related to subsoil class and maximum horizontal acceleration expected in the area and a design vertical pseudostatic coefficient

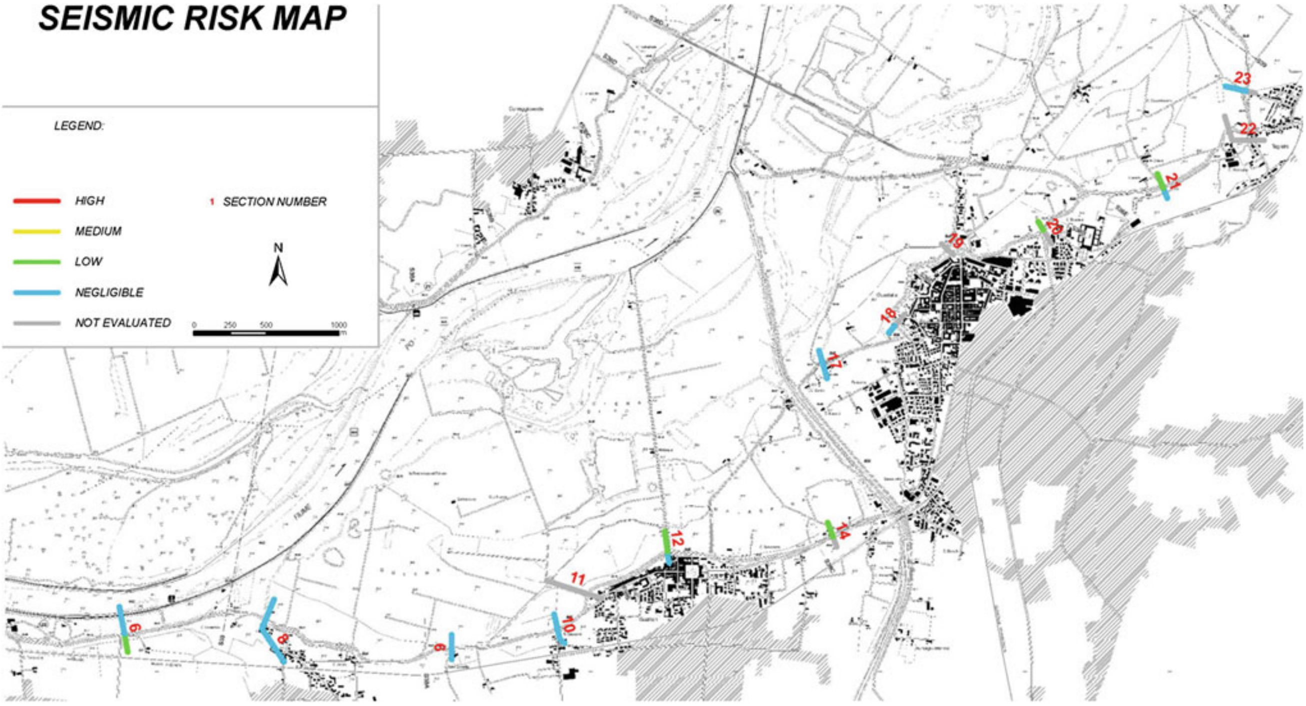

Fig. 150.3 Example of seismic risk map

$K_v = 0.5 \cdot K_h$ was also assumed. All the stability analyses were developed using a probability distribution of the input soil parameters, derived from the interpretation of the CPTU data. Then, a Monte Carlo procedure was applied to evaluate a probability distribution of the resulting safety factors.

150.6 Conclusions: Risk Maps

The results of an extensive investigation of the static and seismic stability conditions of more than 90 km of river-banks along the most important Italian river were presented. The research included the local site response, evaluation of the liquefaction hazard and stability analyses of the river banks. The overall seismic risk was finally evaluated crossing the results of liquefaction and stability analyses of the river banks (Fig. 150.3).

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