Methodological approach for the stability analysis of the Po river banks

Méthodologie pour l'analyse de la stabilité des digues de la rivière Pô

Gottardi G.[1], Madiai C.[2], Marchi M.[1], Tonni L.[1], Vannucchi G.[2]
[1]*DICAM University of Bologna, Bologna, Italy*
[2] *DICEA University of Florence, Florence, Italy*

ABSTRACT: The Po River is the major Italian watercourse, controlled with embankments along half its length. The Italian Government has recently funded a number of activities aimed at the seismic hazard control, including the evaluation of the seismic stability of about 90 km of embankments of the Po river. The paper describes the methodology developed in order to identify a number of significant sections, their geotechnical models and the subsequent static and seismic stability analyses. The vast database coming from hundreds of geotechnical investigations within the study area is described. Local seismic hazard and effects of site conditions on the ground motion are taken into account in the definition of the expected seismic action. The safety conditions of the embankments in static and seismic conditions are investigated as a function of the soil parameters variability and considering various relevant river water levels. Eventually, a methodology aimed at developing stability maps of the investigated area based on the data spatial variability is described.

RÉSUMÉ : Le Pô est le cours d'eau le plus important d'Italie, contrôlé par des remblais qui se déroulent pour presque la moitié de sa longueur. Le gouvernement italien a récemment financé plusieurs études visant à évaluer le risque en cas de séisme et, en particulier, les conditions de stabilité des digues de protection du Pô pour une longueur d'environ 90 kilomètres. L'article présente une méthodologie conçue pour sélectionner les sections représentatives à analyser, définir un modèle fiable du sous-sol, évaluer le risque de rupture des berges en conditions de chargement statique et sous sollicitation sismique. On décrit l'ensemble des plusieurs données comprenant plus de 300 essais de pénétration statique, une centaine de forages, mesures géophysiques en forage et nombreux essais de laboratoire. Les paramètres significatifs du séisme ont été choisis à partir du séisme prévisionnel ainsi que des conditions locales du site. L'évaluation de la variabilité intrinsèque du sol permet d'utiliser des procédures de calcul probabilistes, de manière que la sécurité des berges est définie en terme de probabilité de rupture plutôt que du facteur de sécurité habituel, faisant référence à différents scenarios de crues.

KEYWORDS: riverbanks, stability analysis, in situ tests, seismic vulnerability, probabilistic approach.

1 INTRODUCTION

With a total length of 652 km across northern Italy, the Po River is the major Italian watercourse (Figure 1). Over half its length is controlled with embankments as protection measures against heavy flooding. 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. If levee failures occur following an earthquake during a high water season, considerable flooding in the Po area will occur.

Figure 1. The course of the Po River.

On the other hand, failures of the river bank under seismic action that occur during the dry season might not immediately lead to flooding but time and resources - generally limited - are unlikely to be adequate before the arrival of the rainy season.

Recently, the Italian Government has funded a number of activities aimed at the seismic hazard control, including the evaluation of the seismic stability of about 90 km of embankments of the Po River, promoted and coordinated by the relevant Authority (Autorità di Bacino of the Po River - AdBPO).

The project mainly aims, via a preliminary extensive survey including site investigation and laboratory testing, at the seismic microzonation of the area with assessment of local site response, at the evaluation of the liquefaction potential and at the stability analyses of the riverbanks, under static and seismic conditions. The paper focuses on the methodology developed in order to identify, along the portion of the embankment investigated, a number of significant sections, their geotechnical models and the subsequent static and seismic stability analyses. The safety conditions of the embankments in static and seismic conditions are investigated as a function of the soil parameters variability and considering various relevant river water levels. A probability distribution was assumed to represent the parameters most affecting the stability and a Monte Carlo procedure was then used to compute the probability distribution of the resulting safety factors.

2 GEOTECHNICAL FIELD INVESTIGATIONS AND GEOLOGICAL MODEL

The subsoil of the Po levees is an alluvial succession originated by the depositional activity of the Po river itself and, locally, of his Apennine tributaries. This sequence consists of a cyclic alternation of coarse soils, prevalently sands in its lower part and silty, sandy and sometimes clayey soils in the upper part. The deposits, of Holocene period (< 12,000 years), have a typical thickness of about 10-15 m and lie on a layer of Pleistocene channel sands, very extended laterally, generally saturated, of thickness ranging from 20 to 50 m. Closer to the embankment, these sands can also be found in the Holocene part of the succession. The groundwater is always at few meters depth from the ground level. The geological substratum of the alluvial sequence typically consists of coastal and marine sands of inferior-middle Pleistocene age. A simplified model of depositional environment of a river system in an alluvial plain area is shown in Figure 2. In order to obtain a homogeneous spatial distribution of the geotechnical information, the survey was initially planned according to a grid of test points distributed at regular intervals (Martelli *et al.*, 2011). The stratigraphic variations were defined through sets of in situ tests aligned perpendicularly to the embankment, each set typically consisting of one test in the floodplain area, one on top and one at the toe of the embankment (downstream). The tests in the floodplain area and at the toe, were located as close as possible to the embankment. Additional investigations were carried out subsequently, to improve the knowledge in some particular areas.

The following field investigations were carried out within the project:

- 70 continuous coring boreholes, between 30 and 50 m deep. 24 of these boreholes were equipped by piezometers up to 50 m for the monitoring of the first confined aquifer; 37 (of which 1 to a depth of 70 m) were equipped for down-hole testing;
- 25 open holes, generally up to about 10 m depth at the toe of the embankment, downstream, equipped with piezometers for groundwater monitoring;
- 4 pairs (1 to a depth of about 75 m on top and 3 to a depth of about 150 m at the toe of the embankment) and 1 triplet of borings (to a depth of about 75 m on top of the embankment), equipped for cross hole testing;
- 298 piezocone tests, to a depth of about 35 m;
- 20 seismic cone penetration tests, to a depth of about 30 m;
- 26 down-hole on top and 11 down-hole tests at the toe of the embankment, together with 4 cross-hole tests (one with three holes);
- 3 seismic refraction profiles by MASW and ReMi tests;
- 10 electrical resistivity tests across the embankment;
- about 400 single station recordings of environmental vibrations, half on top and half at the toe of the embankment.

A total of 107 sections (99 cross-sections and 8 longitudinal to the embankment), intercepting when possible, the available tests, were selected and drawn at a scale of 1:2,000 with 5 times vertical exaggeration (Martelli *et al.*, 2011). The main lithological units corresponding to sedimentary facies and depositional environments are represented in the sections up to a depth of about 50 m. A typical cross section of the embankment with the relevant geological model is shown in Figure 3. The stratigraphy of the embankment-subsoil system in the studied area can be briefly described as follows. The embankment (Unit Ar*) consists of landfill organized in alternating layers, various thickness, of different soils including sands, silty sands, sandy silts and clayey silts, with sporadic presence of brick fragments. Strong similarity between the material composing the embankment and the underlying natural levee soils were evidenced from continuous core drilling boreholes; therefore, the location of the stratigraphic boundary is often uncertain in the absence of specific elements (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. 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). The grain size distribution of such sandy deposits, generally of 20-30 m thickness or greater, vary from medium fine to coarse and very coarse, with local presence of gravel, their thickness being. An important aquifer, generally confined, is there located; however, near the levees and the floodplain area, the two aquifers (phreatic and confined) sometimes merge.

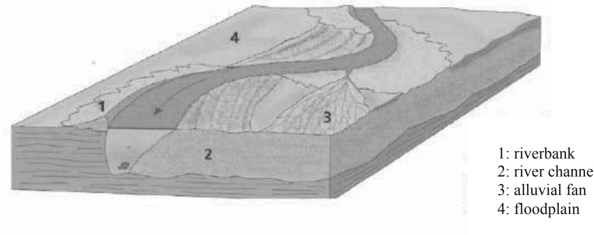

Figure 2. Depositional environment of a river system in an alluvial plain.

3 IDENTIFICATION OF SIGNIFICANT SECTIONS

A specific methodology was developed in order to select a number of significant sections for the stability analyses. Five geographical "macro-areas" were first identified in the 90 km of embankments investigated. The relevant significant sections for the subsequent stability analyses were then selected following a criterion of representativeness and uniform distribution along the river, hence not only the most critical. The embankment features considered to identify the typological groups are:

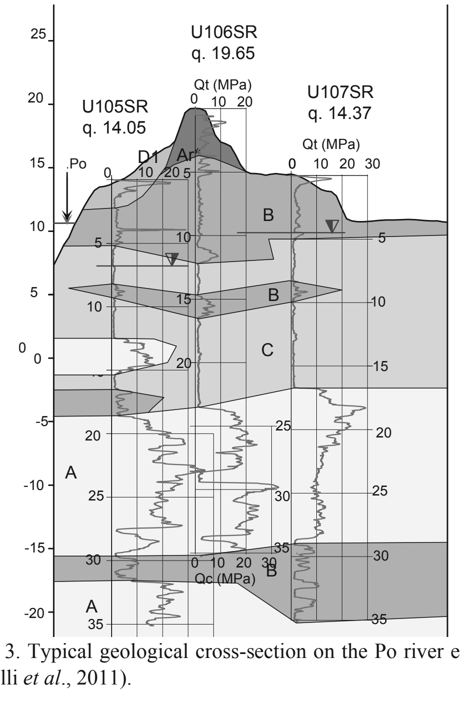

Figure 3. Typical geological cross-section on the Po river embankment (Martelli *et al.*, 2011).

- the geometry of the embankment (Figure 4): in particular, the height (variable from 2 to 23 m) - upstream and downstream - and the number of berms;
- the kind of foundation soil, upstream and downstream;
- the seismic input from local site response;
- the presence of a diaphragm wall at the embankment toe, downstream;
- the reported historical failures.

A total of 43 significant sections was finally selected for the stability analyses.

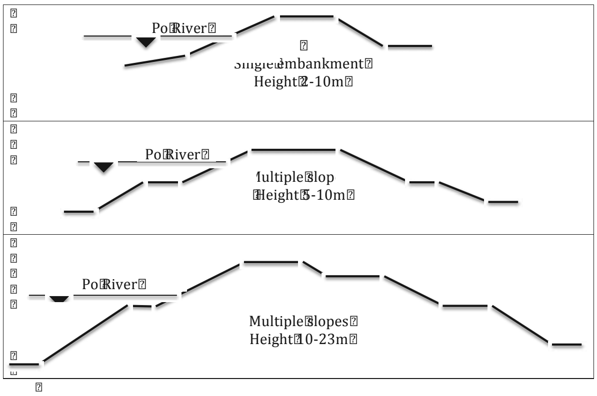

Figure 4. Typical geometries of the Po riverbanks.

4 GEOTECHNICAL CHARACTERIZATION

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 addition, laboratory test results were used as supporting reference data in order to validate the CPTU-based correlations adopted in estimating the relevant soil parameters. In this 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. As an example, Figure 5 provides a typical output of the method, consisting in a profile of the different Soil Behaviour Type (SBT) classes detected along the vertical in conjunction with the CPTU-based material index I_{cn} values. The analysis of such profiles allows identifying a number of homogeneous soil layers, which generally turn out to agree fairly well with the available geological classification. According to the analyses carried out so far, the following typical soil units were identified:

- Unit A_r, a complex alternation of different, predominantly coarse grained sediments such as sands, silty sands, silts to clayey silts, forming the riverbanks;
- Unit A, sand;
- Unit B, predominantly silty sediments (*SBT* zone 4), with sandy and clayey lenses.
- Unit C, predominantly clayey sediments (*SBT* zone 3), with occasional presence of peat and organic soils (*SBT* zone 2).

Geotechnical properties describing soil state, stress history, deformation and strength characteristics were derived from piezocone tests using empirical correlations. Attention was particularly focused on the estimate of the effective stress strength parameters to be used in the stability analyses, hence various transformation models were considered in order to relate test measurements to the most appropriate soil property value. As regards friction angle in sands, empirical relationships relying on relative density were considered, together with the well-known normalized cone resistance-based correlations proposed by Robertson & Campanella (1983) and later by Kulhawy & Mayne (1990). In fine-grained soils, the effective stress friction angle was determined from the normalized CPT readings $Q_t = (q_t - \sigma_{v0})/\sigma'_{v0}$ and $Bq = \Delta u/(q_t - \sigma_{v0})$ (Senneset *et al.* 1989). It is worth observing that, in order to develop a probabilistic stability analysis of riverbanks, the adopted soil characterization procedure includes a rather straightforward method for the assessment of inherent soil variability. According to such approach, the geotechnical property variability is concisely described by the coefficient of variation (Phoon & Kulhawy, 1999). Thus, the geotechnical characterization of each soil unit needs the definition of the mean value of the soil property together with the associated standard deviation *SD* and coefficient of variation *CoV*. From the interpretation of the large amount of available data, it turns out that unit A is typically characterized by a mean friction angle $\varphi'_m = 35°÷36°$ and a standard deviation SD $\cong 2°$; unit B by $\varphi'_m \cong 32°$and SD $\cong 1°$, unit C by $\varphi'_m \cong 24°$ and SD $\cong 2°$. Finally, as regards the sandy-silty mixtures forming the riverbanks, typical values of mean friction angle φ'_m are 32° with a standard deviation SD $\cong 1.5°$.

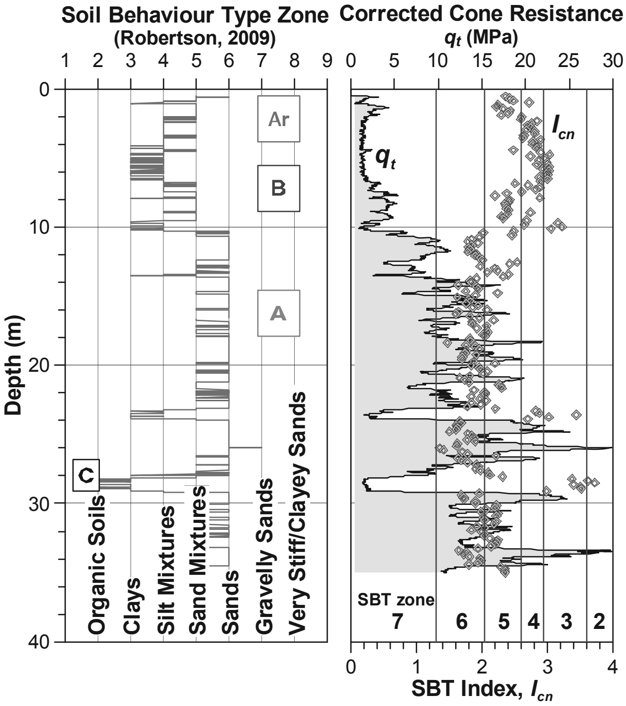

Figure 5. Results from CPTU-based classification

5 LABORATORY TESTING

In order to verify the reliability of the CPTU-based empirical relationships adopted in the study and the intrinsic variability of the geotechnical properties, estimated for each lithological unit, laboratory tests were performed on undisturbed samples taken at different depths and from boreholes even very distant to each other. Seventy undisturbed samples were analyzed, 19 from lithologic Unit Ar*, 17 from Unit B, 16 from Unit C, 2 from Unit D2 and 16 from Unit A. Laboratory testing program included identification and classification tests, oedometric tests, different types of shear strength tests (Direct Shear Test, DST, and triaxial tests, TxCIU, TxCID), resonant column (RC) and torsional cyclic tests. The experimental results from the representative samples of lithologic Units Ar* are shown in Table 1. In particular, for each property, the number of tested specimens, mean, minimum and maximum values, standard deviation and coefficient of variation are reported. Kind of testing, number of specimens, values of the parameters and correlation coefficients are provided for drained and undrained shear strength and for normalized shear modulus and damping ratio versus shear strain relationships.

Table 1. Geotechnical properties from laboratory testing for lithologic Unit A_r*.

	No	*Mean*	*Min.*	*Max.*	*SD*	*CoV (%)*
w_L (%)	51	43.9	27.9	89.4	13.8	31.4
w_P (%)	51	25.3	18.9	43.7	5.3	21.0
I_P (%)	51	18.6	5.8	49.0	9.7	52.1
γ (kN/m^3)	25	19.0	17.8	22.6	1.2	6.1
Gravel (%)	48	0.2	0.0	3.0	0.7	311.6
Sand (%)	48	30.0	0.0	99.5	31.9	106.5
Silt (%)	48	49.2	0.0	79.0	22.7	46.2
Clay (%)	48	20.6	0.0	77.0	17.2	83.7

Effective Stress Envelope: $\tau = c' + \sigma' \tan\phi'$

Type test	*No*	*c' (kPa)*	*tanϕ'*	*ϕ' (°)*	*R^2*
DST	21	5.8	0.472	29.2	0.947
TX	8	0.0	0.525	33.2	0.976

Shear strength envelope (end of test): $\tau = c_R + \sigma \tan\phi_R$

Type test	*No*	*c_R (kPa)*	*tanϕ_R*	*ϕ_R (°)*	*R^2*
TX_CIU	7	15.0	0.453	24.4	0.851

G/G_0 vs. γ: $G/G_0 = 1 / (1 + \alpha \gamma^{\beta})$

Type test	*No*	*α*	*β*	*R^2*
RC	1	23.29	1.105	0.978

D vs. G/G_0: $D = D_{max} \exp(\lambda G/G_0)$

Type test	*No*	*D_{max}*	*λ*	*R^2*
RC	1	44.58	-2.369	0.991

6 STATIC AND SEISMIC STABILITY ANALYSES

Limit equilibrium analyses for assessing the stability of the riverbanks were performed under both static and seismic conditions, as shown in Figure 6 by way of example. The ordinary and the maximum water levels (peak flow) were considered in static effective stress analyses, with steady seepage flow inside the embankment. The method o Morgenstern and Price (1965) was used in the analyses. Th rapid drawdown condition was also considered for the upstream slope of the embankment. Since a complete drawdown is unlikely for a river, the actual water level drop during drawdown was deduced from hydrographs recorded in specific sections of the Po River in the last ten years. A partial drawdown of 8 m from the peak level was thus considered. The simple and conservative effective stress approach was applied in the drawdown analyses but, for the most critical situations, further analyses will be developed using a staged undrained strength method (Duncan et al., 1990). Dynamic effects in the seismic condition were considered using the pseudostatic method and, in this case, an ordinary water level. The values of the (deterministic) factor of safety obtained for the most critical conditions (upstream/downstream) on the section shown by way of example are given in Figure 6. It is worth observing that the most critical situation occurs during rapid drawdown for the upstream slope and during earthquake shaking for the downstream slope.

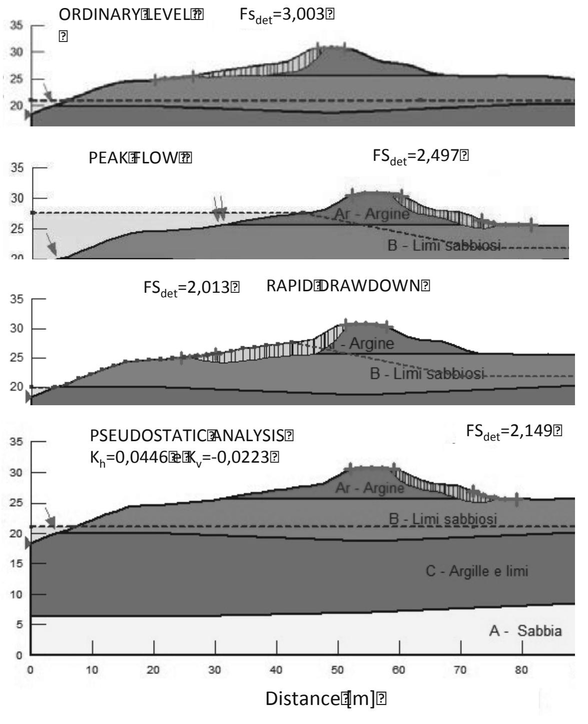

Figure 6. Typical output of deterministic stability analyses in static and seismic conditions.

All the stability analyses were also developed following a probabilistic approach. A probability distribution was assigned to the input soil parameters using the result of the CPTU data interpretation, and then a Monte Carlo procedure was applied to evaluate a probability distribution of the resulting safety factors, a more suitable way of assessing the risk level of instability of each specific section.

7 CONCLUSIONS

The preliminary results of an extensive investigation of the static and seismic stability conditions of more than 90 km of riverbanks along the most important Italian river have been presented. The research included comprehensive experimental field and laboratory geotechnical surveys. However, the length of riverbanks considered together with the complexity of the available experimental database required to develop a methodology aimed at identifying the most representative sections where focusing accurate stability analyses, based on the probabilistic distribution of the main geotechnical parameters. The final goal is to take into account the spatial variability of soil units with a common geological origin and repetitive features, in order to extend the results of the stability analyses and to provide suitable risk maps of great relevance for the management of such vital infrastructure.

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