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and Symposium in Honor of Clyde Baker

STABILITY ANALYSIS OF THE SERCHIO RIVER FLOOD PLAIN EMBANKMENTS (TUSCANY, ITALY)

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ABSTRACT

Following the geotechnical characterization of 30 km long flood - plain embankments of the Serchio River (Tuscany – Italy), a number of numerical analyses have been carried out. The embankments have been constructed since the XVIII century and have experienced several failures in the years (the last in December 2009). The geotechnical characterization of the river embankments and the 2009 flood are described in a companion paper in this Conference. This paper shows the results of numerical analyses that have been carried out for various purposes.

More specifically, the numerical analyses were carried out a) to clarify the causes of the December 2009 failures, b) to design appropriate repair of the failures and retrofit of the embankments in proximity of the failures (about 6 km) and c) to identify the most risk areas considering the whole extension of the embankments (30 km).

The limit equilibrium method was used to assess the stability of the embankments under steady state flow conditions (areas close to the failures). For this analysis three different types of commercial software were used. The stability analyses were carried out using the Bishop simplified method with circular sliding surfaces. The different codes indicated very similar failure surfaces corresponding to the minimum (meaningful) values of the global safety factor. Some differences on the values of the global safety factor were observed by comparing the results obtained from the three codes. More specifically, the analyses results show that, for the selected cross sections, the safety factors are rather small and approaching to unity, if the seepage forces are not considered. In the case of steady state flow, safety factor drastically reduces becoming lower than one. This result apparently contradicts the fact that the considered embankments are standing up since centuries and failures occurred only in the occasion of floods.

The FEM analysis (PLAXIS Flow) shows that the safety margins of the considered sections, in absence of filtration, are assigned to the partial saturation of the embankment. Unfortunately, an appropriate characterization of the material under conditions of partial saturation was not available. Therefore, the FEM analyses were also aimed at determining the necessary time to approach the steady state flow conditions. For the case under consideration it was estimated that 10 days are necessary to approach the steady state flow conditions. This time is apparently much longer than the duration of the longest flood event (few hours). From the above it is possible to conclude that the hypothesis of permanent flow is generally too cautious. Anyway for the failures under consideration, that have occurred with the concurrence of various adverse factors like the melting of the snow because of a sudden temperature increase and the contemporary long raining period (two consecutive floods), it is reasonable to assume that the permanent flow conditions were probably reached.

In addition to the numerical analyses, evidences of the considered event and the susceptibility of the analyzed soil to piping phenomena have also been considered to find out all the possible causes and to design in an appropriate way both repair of the failures and retrofitting of the surrounding areas. Assessment of the most risky areas, considering the whole extension of the embankments (30 km), has been carried out following expeditious criteria which were based on the embankment geometry and the mechanical soil characteristics.

INTRODUCTION

Following the geotechnical characterization of 30 km long flood - plain embankments of the Serchio River (Tuscany, Italy), a number of numerical analyses have been carried out. Indeed, the Geotechnical characterization was aimed at giving a stratigraphic and geotechnical model. The numerical analyses were carried out for different purposes: a) individuating the possible causes of the failures (about 300 m), the necessary repair and the consolidation methods to be adopted for the embankments close to the failures; b) individuating the most risky areas of the remaining 24 km of embankments.
Assessment of possible causes of the December 2009 failures was necessary in order to plan the repair works and the measures to be taken to improve the safety conditions in the proximity of those failures (about three km in the Lucca District and three km in the Pisa District).
The investigations in the remaining part of embankments was aimed at individuating the most risky areas in order to plan the necessary economic resources for later works.

The analyses were carried out considering both stationary flow and limit equilibrium method (SLIDE 2011, Geostudio 2011, PCSTBL 1988) and non - stationary flow and Finite Element Method (PLAXIS 2010). The results of the analyses are reported in the following.

POSSIBLE CAUSES OF THE DECEMBER 2009 FAILURES AND COUNTERMEASURES

Earth river embankments can experience ultimate limit state for one of the following causes (AIPo 2004, 2007, Colleselli 1994, US Army Corp 2000):

- External erosion of river embankments due to:
  - Overtopping;
  - Scouring;
- Internal erosion (seepage, piping);
- Hydraulic Heave failure;
- Mechanical failure due to:
  - Excess of driving stresses in comparison to the available strength;
  - Excessive settlements of the embankments or the subsoil;
- Accidental actions due to the clash against the embankment of boats or other floating bodies.

The case study refers to flood plain embankments that did not experience any overtopping. Therefore the possible causes are restricted to mechanical instability, hydraulic heave failure or internal erosion. It is quite obvious to remember that a numerical analyses based on a deterministic approach is possible only for heave failure or mechanical instability.

Piping is one of the most dominant failure mechanism for both dams and river embankment. In fact piping erosion is considered as the main cause of failure of earthen hydraulic structures. Actually some complex prediction models are available (Sibille L. et al., 2012) but there aren't many numerical methods usable in practice for a deterministic evaluation of piping potential.
Traditional methods to investigate internal erosion susceptibility are mostly based on consideration about particle size distributions and on laboratory tests as jet erosion tests (Mercier F. et al. 2012).
Moreover using conventional monitoring systems it is difficult to detect internal erosion at an early stage. Recent developments have led to fiber optic based monitoring solutions based on distributed temperature measurements that detect and localize leakages (Beck Y.-L. et al., 2012) and to monitoring system based on resistivity measurements (ERI Method, Palma Lopes et al., 2012).

It is interesting to point out the most relevant aspects related to the three possible failure mechanisms as follows.

Mechanical instability

- CAUSES:
  - Low undrained and/or drained shear strength of the earth embankment (or the foundation soil) and increase of the driving forces because of water filtration;
- SOLUTIONS:
  - Improving soil strength;
  - Modifying the embankment geometry;
  - Stabilization works (e.g. retaining structures)

Failure by hydraulic heave

- CAUSES:
  - Hydraulic conditions that can induce zero effective geostatic stress in soils having a medium – high permeability;
  - Soils in loose or very loose conditions;
- SOLUTIONS:
  - Drainage wells or filters on the country side;
  - Use of sheet piles or diaphragm walls to reduce the hydraulic gradients.

Internal erosion (piping)

- CAUSES:
    - Soil heterogeneity (inclusion of coarse material);
    - Grain size distribution of the soil which is prone to erosion phenomena;
    - Low density of the soil;
    - Facing not capable to avoid the phenomenon.
- SOLUTIONS:
    - Use of sheet piles, diaphragm walls or other types of barriers to avoid filtration and consequent transportation of soil particles.

Internal erosion (Piping)

As for the case under consideration there are evidences that internal erosion could be one of the possible causes (see Figure 1 showing the water flow through the upper part of the embankment at Nodica during the December 2009 flood).

Fig. 1. Water flow through the upper part of the Serchio river embankment at Nodica during the December 2009 flood (Autorità di Bacino Fiume Serchio, 2010).

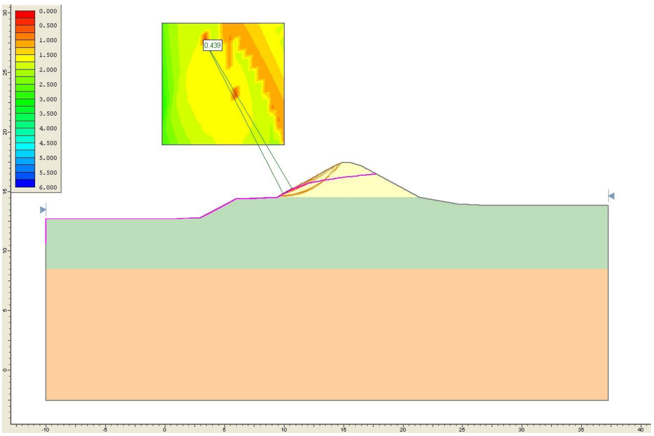


Fig. 2. Typical cross section of the Serchio river embankment in proximity of the December 2009 failures, analyzed by software SLIDE .

As for the soil susceptibility to piping it is worthwhile to remember that mainly fine sands and silty sands are soils susceptible to piping. For finer soils the stability is guaranteed if $D_{15} < 0.4$ mm and $U_c < 20$ (Cedergren 1967). On the other hand, according to Terzaghi and Peck (1967) the above rules that have been developed for soil filters do not apply to well constructed embankments. Indeed, according to Terzaghi and Peck (1967) in this case the water flow through the bank is minimum and quasi non – existent.

Unfortunately, the embankments under consideration were mainly constructed before Terzaghi (since XVIII century) and there are no evidences of the construction details and possible anomalies inside the embankment body. Besides there are clear evidences that piping occurred, at least in one case, during the 2009 event.

Grain size analyses indicate that:

- for all the analyzed samples $D_{15} < 0.4$ mm
- U_c is generally between 6 and 50
- extreme values of U_c are 2.4 (one sample) and 70 to 90 (5 % of analyzed samples)

The analyzed soil does not seem to be particularly prone to piping phenomena but it should be remarked that investigations concern a limited number of boreholes and it is not possible to exclude the presence of anomalies within the embankment.

Mechanical failure and hydraulic heave

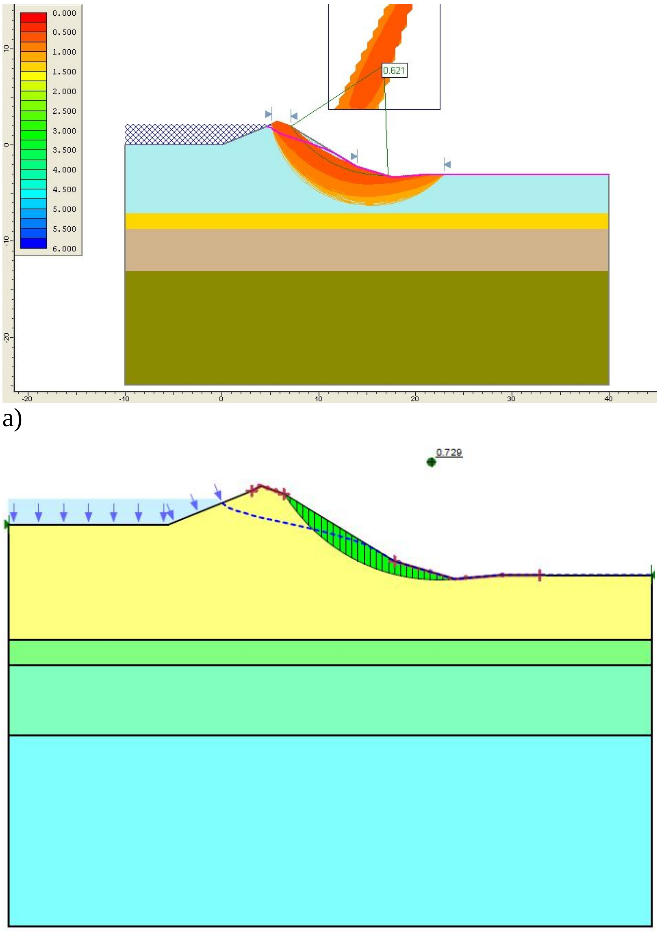
Figure 2 shows the typical cross section of the embankment in proximity of the December 2009 Failures and the stratigraphic/geotechnical model that have been adopted for the Limit Equilibrium Analyses. Analyses were carried out using simplified Bishop method and considering stationary flow with the water level coincident with the embankment crest on the River side and with the GL on the country side. Under these conditions safety factors lower than 1 have been obtained. In addition, the safety condition against potential heave failures does not respect the prescriptions of the Italian Building Code (NTC 2008). More precisely, the water pressure (u) on the country side is similar to total vertical geostatic stress not respecting the following equation (NTC 2008):

$$1.1 \cdot u \leq 0.9 \cdot \sigma_{v0} \qquad (1)$$

The above condition has been checked at the nodes of the mesh used for seepage calculation. It seems obvious to conclude that stability (mechanical & hydraulic) of these embankments becomes critical under the circumstance of stationary flow which implies complete saturation of the soil.

Figures 3a and 3b show the results of the above analyses carried out using SLIDE (2010). Similar results have been obtained using the code SLOPE/W, SEEP/W GeoStudio (2007).

The validity of stationary flow condition is analyzed in the light of the results obtained with FEM analyses (PLAXIS, 2010) in order to clarify how realistic is this hypothesis.



a)

b)

Fig. 3. Example of results of the stability analyses carried out using SLIDE (a) and both SEEP/W and SLOPE/W (b). (Section: 9dx).

FEM analyses, using PLAXFLOW module of PLAXIS, have been carried out mainly for two purposes: a) to investigate the influence of advance of saturation front within embankment body, b) to evaluate the effectiveness of the adopted countermeasures that are described in detail in the next paragraph.

In order to evaluate stability conditions against failures, FEM analyses have been carried out assuming a simple Mohr-Coulomb constitutive model. The strength parameters were the same used for the stability analyses described above and carried out with the Limit Equilibrium Method. The stiffness of the materials was chosen very high in order to put in evidence the differences due to partial saturation.

Since a characterization of partially saturated soil was not available, the default parameters proposed by software library have been used. The default parameters were inferred from grain size characteristics.

In spite of software capability, the transient flow was analyzed with reference to time history of water level in the flood plain. In particular a constant water level coincident with the embankment crest was considered for duration of 10 days. This time is longer than real duration of flood for the Serchio River, which is of few hours long. This duration was fixed in agreement with Lucca District Officers in order to apply a sort of stress test for the embankments. In fact, as reported above, all the sections analyzed in steady state condition indicate a global safety factor smaller than one. Therefore it was not possible to define a list of priority for the interventions, based on the described numerical analyses.

The flood that caused three failures in 2009 was quite usual in terms of River discharge. It is worthwhile to remark that during the event the maximum water level never reached the crest of the embankment. Table 1 summarizes the observed maximum discharge of the Serchio River for different flood – events.

Table 1 Maximum Discharge of the Serchio River for various past flood – event

Flood - event	**Maximum River Discharge m^3/s**	**Embankment failure**
November 9th 1982	2000	NOT
November 1st 2000	1580	NOT
November 9th 2000	1580	YES (*)
December 5th 2008	1025	NOT
December 10th 2009	1200	NOT
December 25th 2009	1900	YES (*)

(*) Repeated floods in 10 – 15 days during 2000 and 2009 events produced embankment failures in the same areas.

It is worthwhile to remark that the embankments under consideration survived to most of the past events but not to the 2000 and 2009 floods. The occurrence of two floods in two weeks and the occurrence (very rare) of snowfalls in between the two floods with snow melting because of sudden temperature rise is the peculiar characteristic of the 2009 event. In the light of the analyses that have been reported above, the contemporaneity of all these adverse factors concurred in determining the failures. By the way, the occurrence of two floods in ten days on November 2000 caused the embankment failures in the same areas as in 2009.

It seems that the embankment saturation degree is more relevant than the River Discharge. Nevertheless the lack of unsaturated soil characterization reduces the meaning of a back analysis, which needs to take into account all boundary conditions changes.

Figure 4 shows the results of the described analysis carried out for section 9. The blue line indicates the upper limit of saturated zone, whereas the color map indicates the mobilized shear strength (dark red, full mobilized).

The body of embankment remains unsaturated and the color map indicates the absence of collapse mechanism. The φ-c reduction procedure indicates a safety factor greater than 1, even if this information has only a relative meaning.

The situation depicted in figure 4 is representative of all analyzed sections (see as an example the results shown in figure 5 for section 25).

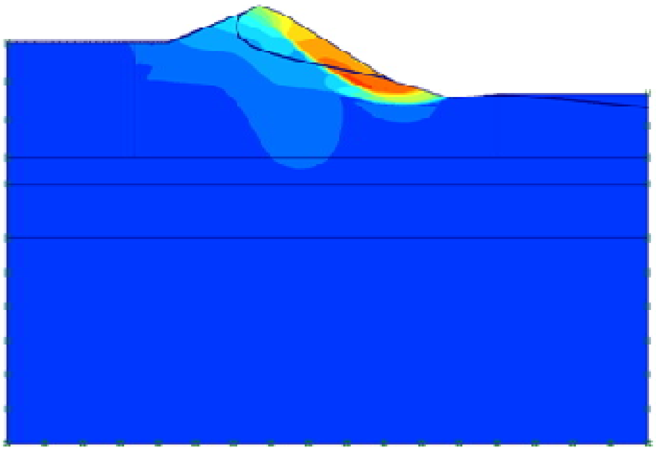


Fig. 4. Results of transient flow analysis for section 9.

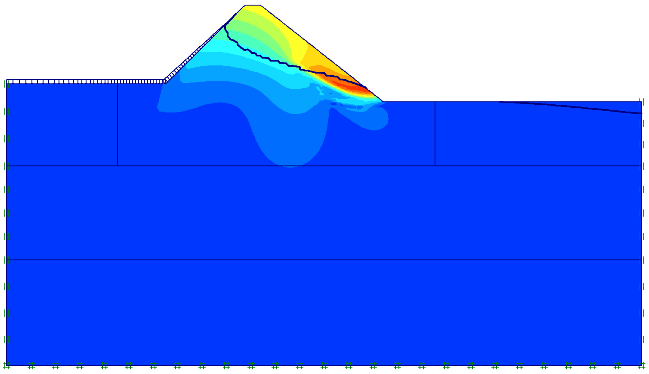


Fig. 5. Results of transient flow analysis for section 25.

The same procedure was applied to evaluate the countermeasures that have been adopted for the embankment refurbishment. In order to have a rapid increment of safety against floods, the Lucca District Officers proposed to install a metallic sheet piles diaphragm within the body of the embankment. In this case analyses were carried out in order to optimize the diaphragm height. As shown in figure 6, the effect of the diaphragm was a reduction of saturation zone by about one meter. This effect was practically the same even changing the height of diaphragm because of the presence of a high permeability stratum at shallow depth. Since the diaphragm base was inserted in this stratum, any increment of diaphragm height was ineffective. In figure 6 the situation for refurbished section 25 is reported, in which is evident the addiction of a berm. The color map indicates the degree of saturation.

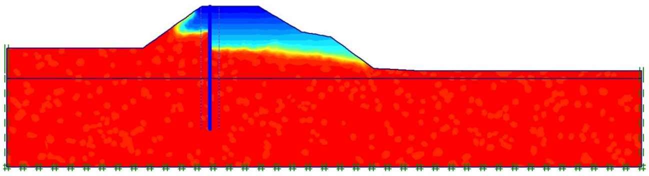


Fig. 6. Results of transient flow analysis for new section 25.

Countermeasures

As for the countermeasures to be adopted in the proximity of the December 2009 failures it was decided to install a 10 m deep sheet pile barrier along the embankment, located at the centre of the embankment cross section. In addition the geometry of the cross –section has been modified as shown for the section 25 by comparison between Figure 5 and 6.

The extension of the embankments to be consolidated (about 3 km in the Lucca district) has been decided on the basis of vulnerability criteria, that is to protect the most vulnerable part of the territory. The installation of the sheet pile barrier has been decided to prevent piping phenomena and reduce the risk of mechanical and/or hydraulic failures of the embankment. In addition the sheet pile wall should guarantee a protection of the territory immediately after erosion of the banks due to overtopping. Indeed the embankments have been designed to protect the territory against a flood with a 30 years return period. Overtopping should occur for floods with higher return periods.

The beneficial effects of the sheet pile barrier is discussed in the chapter on FEM analyses.

MAPPING MOST RISKY AREAS

Limit equilibrium analyses were repeated for the remaining 24 km of embankments considering typical cross sections (geometry and stratigraphy), steady state flow condition and the water table elevation coincident with the embankment crest. Table 2 summarizes the values of safety factor as obtained using different types of software for some cross sections. The safety factors reported in Table 2 mainly refer to cross section in critical conditions. It is worthwhile to remark that the old version of PC STBL 5M (1988) does not take into account the seepage (probable reason for higher values of the safety factor obtained with this software). Anyway, previous analyses (FEM analyses) and failure evidences have pointed out the following aspects:

- the 2009 failures are mainly due to the fact that for particular reasons the full saturation of the embankment was reached in that occasion;
- the hypothesis of full saturation of the embankment is quite unrealistic even though the scenario of the 2009 event could repeat in the future especially because of climate changes.

Therefore, in order to individuate the most risky areas, for the remaining 24 km of embankments not yet considered for immediate consolidation works, expeditious criteria have been adopted, instead of numerical analyses. More specifically the critical cross sections to be analyzed have been selected on the basis of geometric criteria or considering the soil strength as inferred from CPTU (Pierotti 2011).

Table 2 Values of safety factor by different software

	Safety Factor		
Section	Slide	PC-Stabl	Slope-W
9 rb L	0.621	0.76	0.729
13 rb L	0.677	0.87	0.655
25 rb L	0.560	0.62	0.640
39 lb L	0.819	0.89	0.898
51 lb L	0.676	0.71	0.710
57 lb L	0.746	0.78	0.798
4 lb P	1.264	1.40	1.318
27 lb P	1.047	1.19	1.132
32 lb P	0.728	0.99	0.760
48 lb P	0.794	1.02	0.828
51 lb P	0.761	1.09	0.763
57 lb P	0.905	0.93	0.906

L (Lucca district), P (Pisa district) lb (left bank) rb (right bank).

The geometric criterion can be synthetized by the ratio between the embankment height and the length of its base. The higher this ratio, the higher the risk of a failure.

On the other hand Figure 7 shows the minimum and maximum envelope of CPTU tip resistance that have been carried out in the 3 km (Lucca district) of embankments close to the December 2009 failures. Since this part of embankment has been recognized poorly constructed, it has been assumed as reference. The Figures 8 show the criterion adopted to define the potential risk of a given portion of embankments on the basis of soil strength.

Figure 9 shows the mapping of the risk areas based on the above criteria.

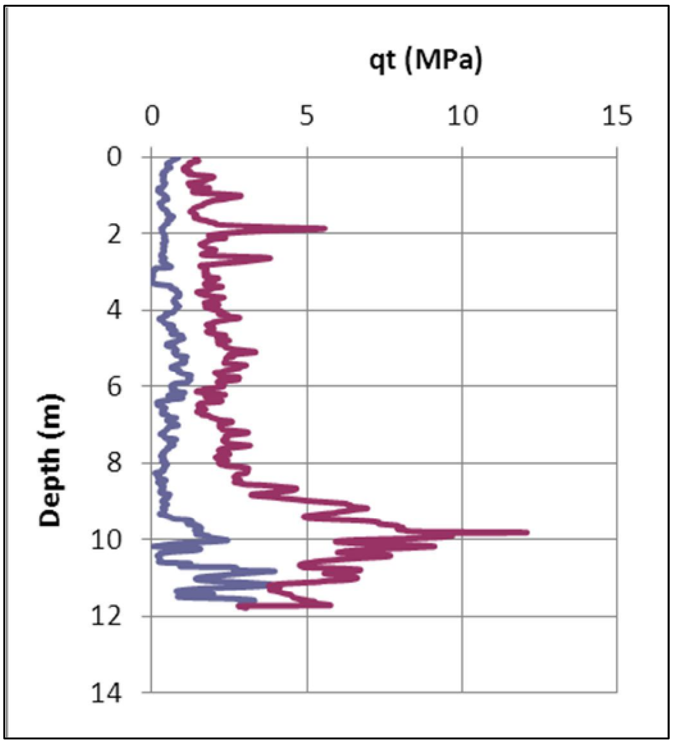


Fig. 7. Minimum and maximum envelope for q_t.

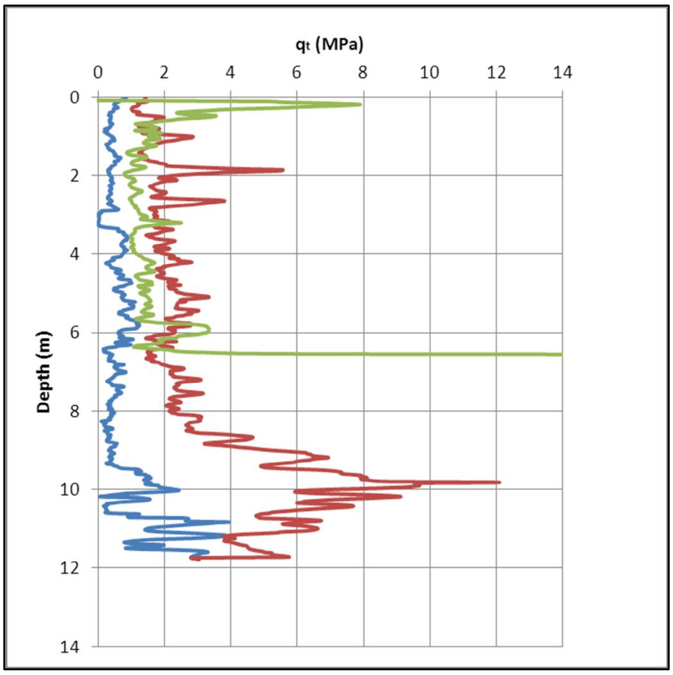


Fig. 8a. Exemplification of second criterion application. a) Risky, b) Not risky

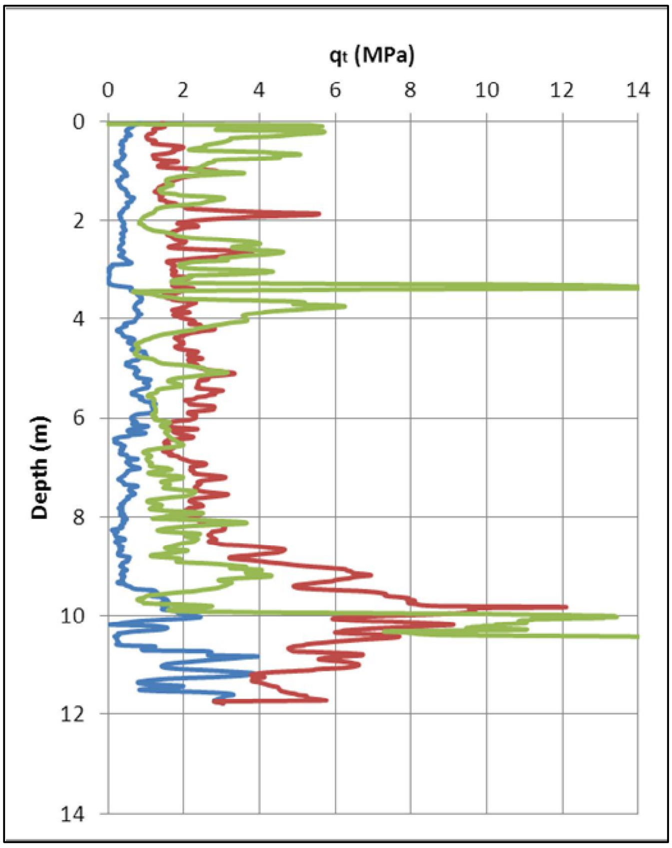


Fig. 8b. Exemplification of second criterion application. a) Risky, b) Not risky

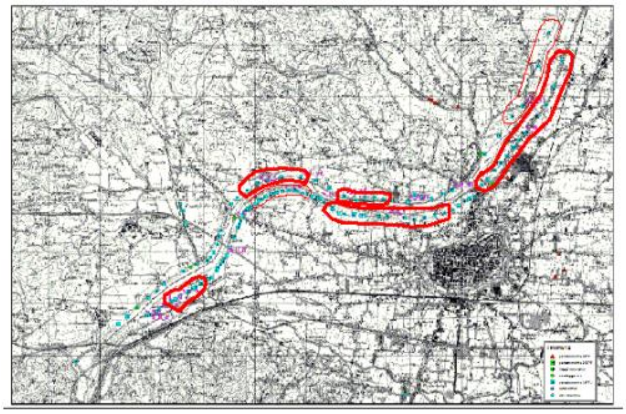


Fig. 9. Map of the risk areas.

CONCLUSIONS

In the paper are reported the results of analyses of the Serchio River embankments carried out by means of different computational tools and under different hypotheses. In particular the flow condition were considered as stationary or transient. For examined cases the different hypotheses change dramatically the results. In the first case none of examined sections can sustain the steady flow. This result is not consistent with experimental evidence: the XVIII century embankments of the Serchio River, although they are quite weak, have often be hit by flood, even more severe than the 2009 event, surviving with some, few exception. As a consequence a steady state can be considered too much conservative or, more appropriately, inapplicable to this case.

A more plausible results have been obtained by means of transient flow analyses. Even if applied in lack of information about partially saturation behavior of soil, the analyses show that the embankments owe their resistance to partial saturation.

In order to obtain a list of priority of future consolidation works an expeditious criterion based on geometry and mechanical characteristics of the soil was applied to various sections. The application of such a criterion let to put in order of priority the zones reported in figure 9.

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