Geotechnical Characterization of the Flood Plain Embankments of the Serchio River (Tuscany, Italy)

Barbara Cosanti
University of Pisa, Italy

Nunziante Squeglia
University of Pisa, Italy

Diego C. F. Lo Presti
University of Pisa, Italy

GEOTECHNICAL CHARACTERIZATION OF THE FLOOD PLAIN EMBANKMENTS OF THE SERCHIO RIVER (TUSCANY, ITALY)

Barbara Cosanti
PhD School of Engineering "Leonardo Da Vinci"
Dept. of Civil Engineering, University of Pisa
Pisa, Italy

Nunziante Squeglia
Department of Civil Engineering
University of Pisa
Pisa, Italy

Diego C. F. Lo Presti
Department of Civil Engineering
University of Pisa
Pisa, Italy

ABSTRACT

The flood plain embankments of the Serchio river have been constructed since the XVIII century and construction details are not known. These embankments have experienced failures several times during their life (last in December 2009). After the last event a detailed geotechnical investigation has been carried out.
This paper discusses the necessary criteria for a cost – effective campaign considering the total length of the embankments (30 km) and the requested level of detail. In fact levee failure, although it is of limited extension, causes the achievement of the ultimate limit state of the entire embankment system.
The campaign, in addition to laboratory tests, included boreholes, CPTu, permeability tests, 2D geo-electric tomography and 15 tests performed by the use of the continuous core drilling system. This last has proved to be a very useful tool for obtaining the more accurate evaluation of the in situ soil density (as confirmed by CPTu results). CPTu test, economical and expeditious, has proved to be an indispensable tool for delineating soil stratigraphy. In fact, their results combined with the borehole logs and laboratory testing provide extensive information. Geo-electric investigations can be very useful to highlight anomalies and heterogeneities in the cross section.
Eventually, it is worthwhile to stress that embankments have generally a height of less than 4 m and a width between 1.2 and 3 m. This has restricted the investigation tools that could be used in this peculiar case.

INTRODUCTION

The flood plain embankments of the Serchio river have been constructed since the XVIII century and construction details are not known. These embankments have experienced failures several times during their life (last in December 2009). These failures occurred during the night of December 25th after the concurrence of various adverse factors like the melting of the snow because of a sudden temperature increase and the contemporary long raining period (Autorità di Bacino del Fiume Serchio, 2010). Three failures of the Serchio River embankments that occurred in that occasion. The two failures that occurred in the district of Lucca near the Town of Santa Maria al Colle had a total length of 100 m. The third failure occurred in the district of Pisa near the urban centres of Nodica and Migliarino and had a length of about 160 m. The failures are located in Figures 1 and 2.
As a consequence of these failures large urbanized areas were flooded with a water plus mud level as high as 2 meter with damages to the constructions and infrastructures. The highway connecting the cities of Genoa and Rome was closed at Pisa for a couple of weeks because of the overtopping and the large settlement of a portion of embankment with the possible risk of further instabilities. Also the State Road SS1 connecting Genoa to Rome was closed between Migliarino and Pisa for several month because of the overtopping and the settlements occurred in a large portion of embankments. Pictures of the failures and of the flooded areas are given in Figures 3 and 4.

The immediate repair of the failures and the consolidation of 3 km of embankments close to the failure zones were decided by the Lucca District and Italian Civil Service. In the mean time the Lucca District (Office for the defense of the Territory) with the Pisa District asked to the Geotechnical Laboratory of the University of Pisa to define and control both a geotechnical investigation for characterization of the three km of embankments to be consolidated and a more extended investigation for the characterization of the remaining 24 km of river embankments. Other three km of embankments were directly investigated by the technical staff of the Pisa district. In addition it was asked to define a stratigraphic and geotechnical model and to carry out a number of analyses for different purposes: a) individuation of the possible causes of the failures and consequent consolidation measures; b) individuation of the most risky areas of the remaining 24 km of embankments.

The analyses were carried out considering both stationary flow and limit equilibrium method and non - stationary flow and Finite Element Method. The results of the analyses are reported in a companion paper. This paper deals with the geotechnical investigations and their interpretation and use.

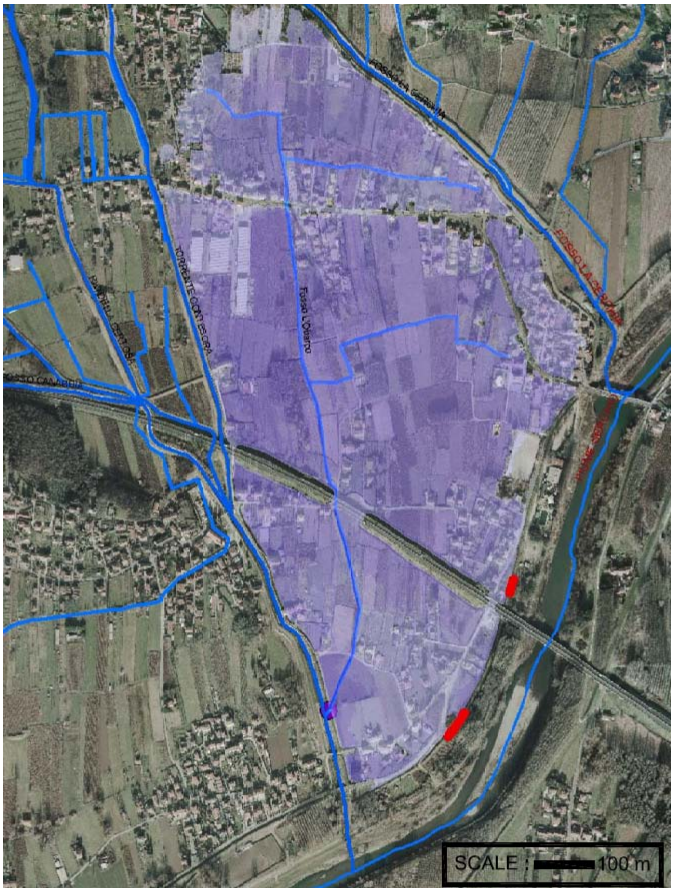

Fig. 1. Failures in the District of Lucca (red lines) and flooded areas.

Because of the long extension of the area to be investigated (totally about 30 km) and the need of information as detailed as much (in fact levee failure, although it is of limited extension, causes the achievement of the ultimate limit state of the entire embankment system) the following geotechnical campaign was decided:

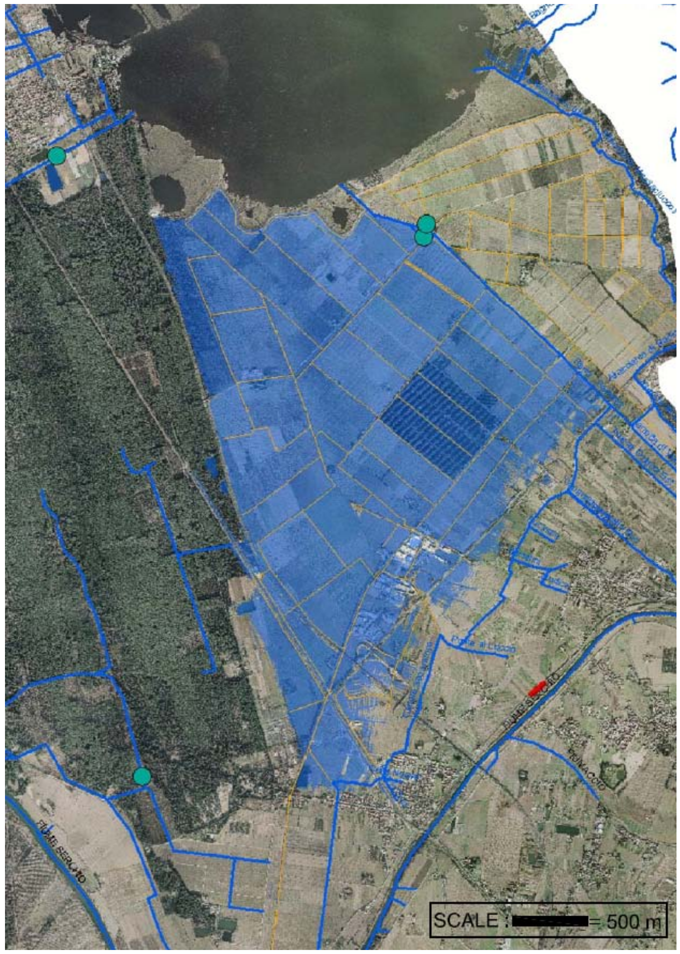

Fig. 2. Failure in the District of Pisa (red line) and flooded areas. (The green points represent draining pumps).

- One borehole (15 m deep) every 1000 m
  - 4 Osterberg samples retrieved from each borehole for laboratory testing
    - Classification
    - Triaxial CIU tests
  - 4 Lefranc tests for each borehole;
  - 2 Casagrande piezometers for each borehole;
- CPTU (15 m deep) every 200 m;
- 2D Electric Resistivity Tomography (ERT) every about 200 m or less;
- 15 Continuous sampling (4 m deep) carried our every 200 m (only for the three km of embankments subjected to consolidation works), using a specially devised micro – stratigraphic sampler.

Fig. 3. Failures and flooded areas in the District of Lucca (Pictures: Italian Civil Service).

For obvious reasons it was decided to have one CPTU and ERT located very close to each borehole. As for the continuous sampling, they were carried out very close to already performed CPTU. Indeed a piezocone was used for CPTU but for the first meters the tip was penetrating a partial saturated soil. The same consideration applies when interpreting the ERTs. It is worthwhile to stress the fact that ERTs were mainly carried out along cross sections of the embankment. Two ERTs were carried out using an electrode – alignment parallel to the river embankment.

It is worthwhile to stress that most of boreholes and CPTU were carried out from the crest of the embankment.

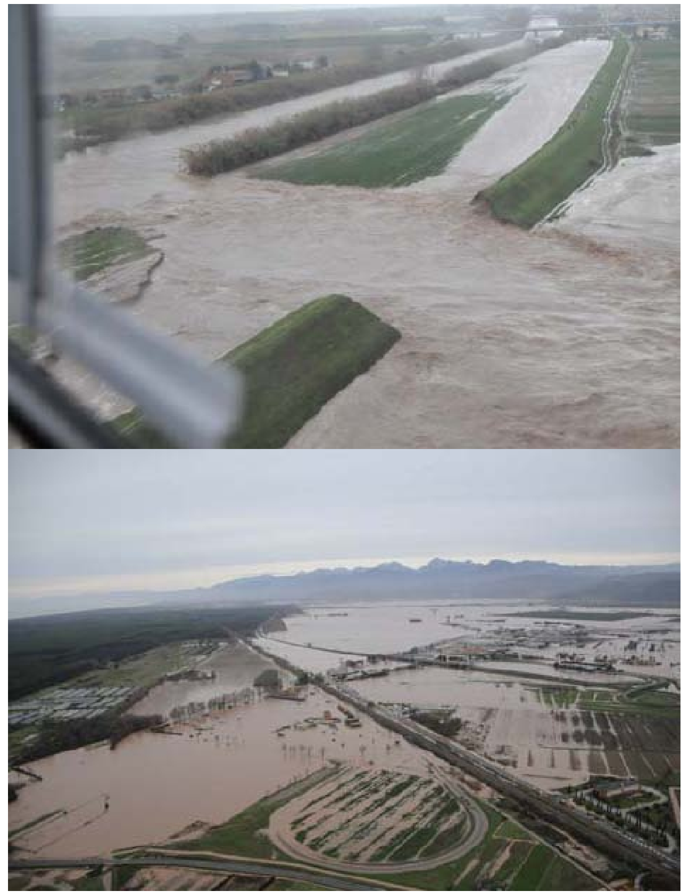

Fig. 4. Failure and flooded areas in the District of Pisa (Pictures: Italian Civil Service).

CONTINUOUS SAMPLING

Continuous sampling has been carried out using a specially devised micro stratigraphic sampler. In particular, the so called AF SHALLOW CORE SYSTEM (Principe et al. 1997), with an inner diameter of 38 mm, has been used. The tests has been carried out down to a depth of 4 m (i.e. the average embankment depth) measuring the sample compaction each 50 cm.

These continuous samples have been used to get a detailed grain size distribution of the soil and to evaluate the in situ soil density. It is worthwhile to stress that this sampling has been carried out only in the "proximity" of the 2009 failures.

The grain size distribution curves will be considered later on. The following values of natural volume weight have been obtained for the main soil textures existing in the body of the embankment:

- Sandy silt to silty sand from 12.3 – 12.8 kN/m^3
- Coarse sand 17.7 kN/m^3

The above reported values are very low but consistent with the

results of CPTU indicating densities of about 10% for the silty sands and sandy silts.
Incidentally the values of the natural volume weight that have been obtained from few Shelby samples (retrieved in the same areas) were much higher than those inferred from continuous sampling. This confirm that for these very loose (mainly granular) soils the only possibility of avoiding soil compaction was to use Osterberg sampler.

ERTs VS. BOREHOLES

ERTs were carried out using 96 electrodes and a 2 Ampere current. The inter – electrodes distance was 0.5 m. A Syscal Pro at 96 channels was used as data acquisition system (So.Ge.T. s.n.c. 2011). The above indicated instrumentation gave the possibility of carrying out expeditious, high precision measurements and to investigate the subsoil down to 15 m.
As for the measurements two different scheme were used: a) Wenner scheme (four – poles) and b) pole – dipole scheme (three poles).
Data interpretation has been carried out by using the software TomoLAB® (2009) based on a FEM mesh. Test results are shown as 2D tomography in terms of resistivity (Ohm*m) using appropriate chromatic scales (Figure 5). In the same Figure the position of the water table is also shown.
The soil stratigraphy that have been indirectly inferred from ERTs has been compared to that directly obtained from the corresponding borehole.
In order to carry out such a comparison, the soil description (soil texture) from boreholes has been uniformed and simplified referring to the Soil Behavior Type (SBT) classes proposed by Robertson (1990). The assumed correspondences between SBT classes, resistivity and soil texture are given in Table 1 (Vannucci 2011).
The % of success of ERTs to give the same classification as from borehole - logs has been computed according to the correspondences of Table 1. The percentage of success is computed for each SBT class as the ratio between the length of correctly identified soil layers and the total length of layers belonging to that class.

Table 1 Correspondences between SBT classes, resistivity and soil texture (Vannucci 2011).

SBT class (Robertson 1990)	Soil Texture	Resitsivity Ohm*m (*)
3	Clay and silty clay	0 – 20
4	Silty clay to clayey silt	20 – 50
5	Sandy silt to silty sand	50 – 130
6	Sand	130 – 500
7	Gravel and coarse sand	≥ 500

(*) For a given class, the lower limit of the resistivity refers to partially saturated conditions

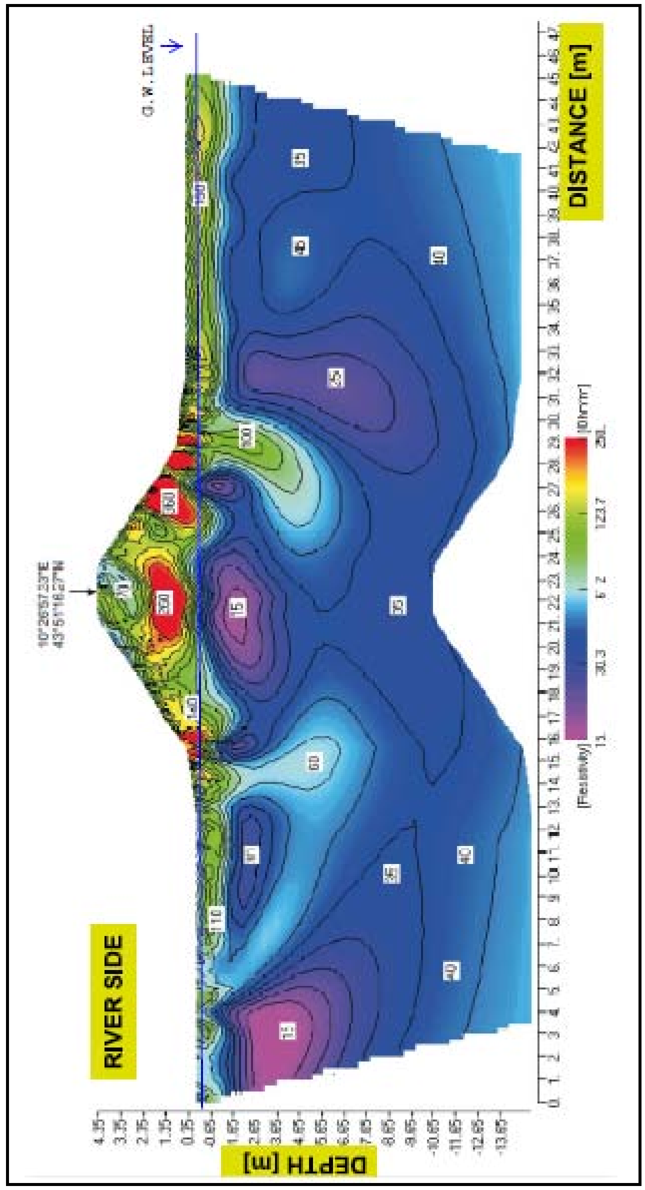

Fig. 5. Example of 2D tomography.

Table 2 and 3 (Vannucci 2011) summarize this evaluation. Table 2 refers to the layers above the water table while Table 3 refers to the layers below the water table.
The columns indicate the SBT classes as from the borehole – logs, while the rows indicate the SBT classes from ERTs. The percentage of success is obviously indicated by the diagonal. The sum of the percentages along a column is 100%. The column 3 is empty because this SBT class is not found in the borehole logs.

Table 2 Percentage of success of ERTs for the layers above the water table (Vannucci 2011).

	3	4	5	6	7
3	0%	0%	3,99%	11,78%	0%
4	0%	0%	19,80%	15,58%	8,42%
5	0%	48,54%	26,21%	37,77%	71,21%
6	0%	51,46%	43,90%	34,87%	20,37%
7	0%	0%	6,10%	0%	0%

Table 3 Percentage of success of ERTs for the layers below the water table (Vannucci 2011).

	3	4	5	6	7
3	0%	0%	0%	2,57%	0%
4	0%	91,53%	65,42%	65,20%	32,98%
5	0%	0%	10,54%	8,32%	25,49%
6	0%	8,47%	2,69%	19,05%	14,39%
7	0%	0%	21,35%	4,86%	27,14%

It is possible to conclude that ERTs have a very low percentage of success for partially saturated soils and in this case the “un - correct” soil identification is quite casual. On the other hand for saturated conditions the percentage of success greatly increase especially for fine soils and the error becomes mainly systematic. In other words ERTs systematically underestimate the soil grain size.
Incidentally the results obtained from the two ERTs parallel to the river embankment are not in agreement with that inferred from ERTs carried out along cross – sections. This confirms that the embankment geometry is not suitable to carry out ERTs along longitudinal sections.

CPTU VS BOREHOLES

CPTU were interpreted using CPTeT-IT program (Geologismiki 2009). Figure 6 shows a typical result based on the Robertson (1990) SBT classification. The percentage of success of CPTU has been computed in a similar way as for ERTs. Table 4 summarizes the comparison. It is possible to conclude that CPTU systematically underestimate the grain size and in most case the soil is classified in the lower class (i.e. 3 instead of 4). Anyway, because the error is quite systematic it is possible to use CPTU after a correct calibration to extend the information obtained from the borehole – logs to a larger portion of investigated soil. Obviously this gives the opportunity of having a detailed SBT description with acceptable costs.

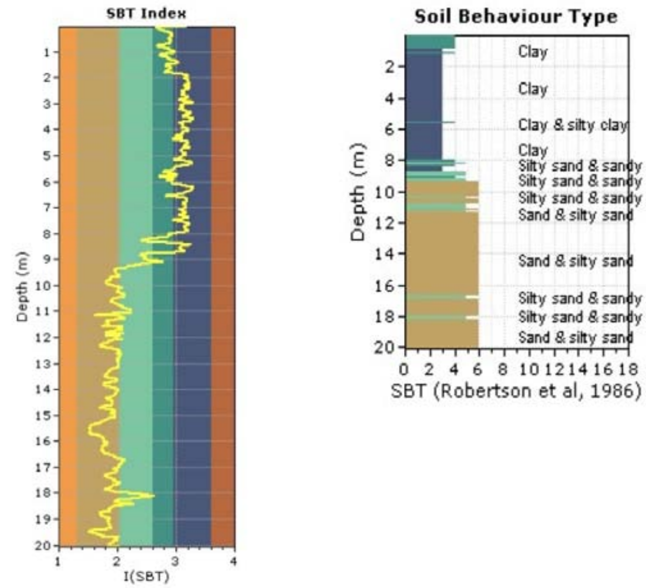

Fig. 6. Typical result of a CPTU interpretation based on the Robertson (1990) SBT classification. (Software: CPTeT-IT Geologismiki).

Table 4 Percentage of success of CPTU (Barba 2011).

	3	4	5	6	7	Other
3	0%	36%	46%	16%	18%	5%
4	0%	14%	30%	15%	7%	18%
5	0%	43%	19%	22%	12%	34%
6	0%	7%	4%	46%	62%	43%
7	0%	0%	0%	1%	1%	0%
Other	0%	0%	1%	1%	0%	0%

Incidentally, CPTU results have been used to obtain the undrained shear strength in fine grained layers and the angle of shear resistance in granular layers. The undrained shear strength has been computed assuming a bearing capacity factor N_{kt} = 14. The angle of shear resistance has been computed using the Schmertmann (1978) equations after the assessment from the tip resistance of the relative density. The relative density was determined according to the empirical approach proposed by Jamiolkowski et al. (1985).

Incidentally the same values of the angle of shear resistance were obtained from triaxial laboratory testing on specimens from undisturbed Osterberg samples. Of course the comparison was possible only for those layers where undisturbed sampling was possible. The obtained soil parameters are summarized in the chapter concerning the Geotechnical Model.

CRITERIA FOR DEFINING A STRATIGRAPHIC MODEL

In order to achieve a stratigraphic model the soil was classified into four groups based on laboratory grain size distributions (Ghini 2010, Pierotti 2011, Fochi 2011). The grain size distribution curves are shown in Figures 7, 8, 9 and 10.

The four groups have been identified in the following way:

- Sand
- Silty sand
- Sand with clayey silt
- Clayey sandy silt

A SBT class and a soil description (as from the stratigraphic log) was associated to each group. In this way the stratigraphic model shown in Figure 11 was obtained.
ERTs were not used in this process because of the intrinsic limitations of this testing method which is very sensitive to the presence of water. ERTs where mainly used to get information on the homogeneity of the cross sections.

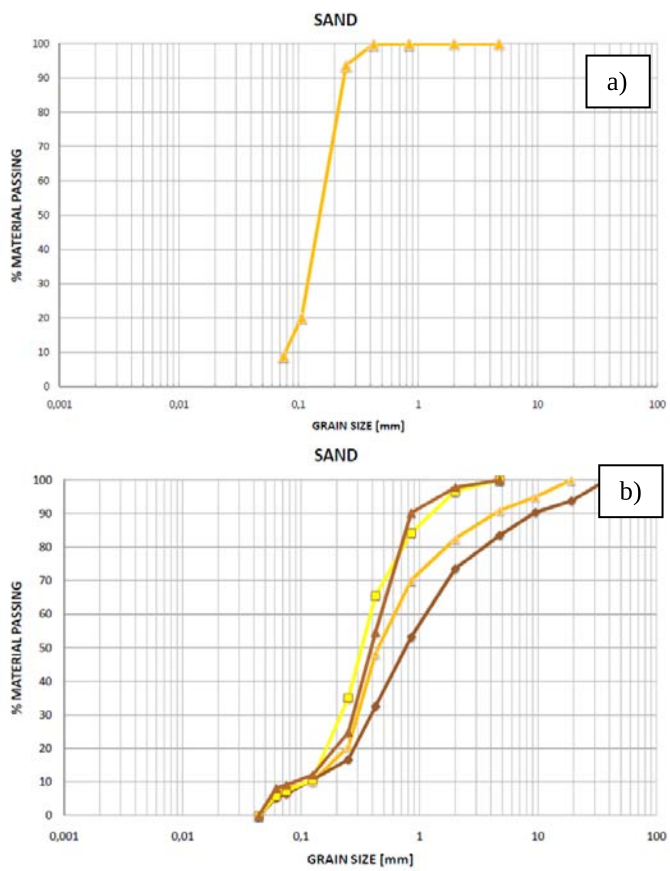

Fig. 7. Grain size distribution curves: sand.
a) District of Lucca; b) District of Pisa.

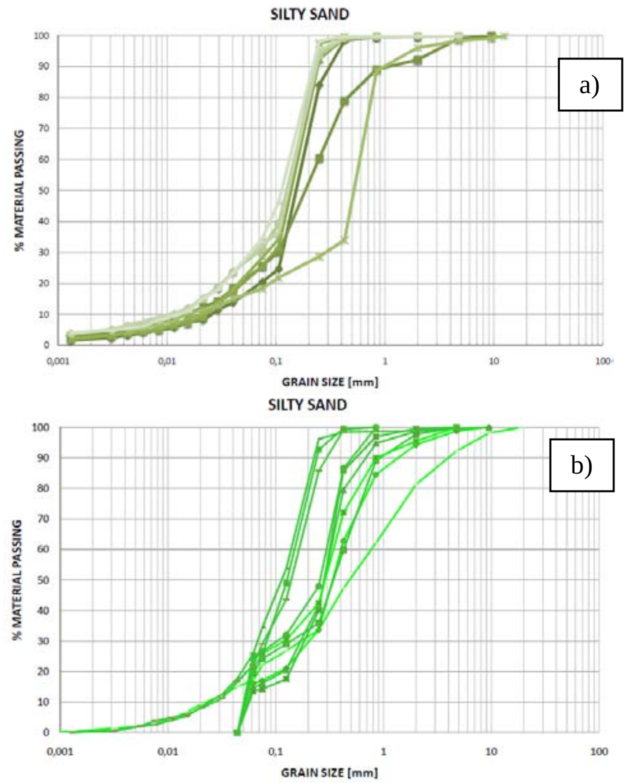

Fig. 8. Grain size distribution curves: silty sand.
a) District of Lucca; b) District of Pisa.

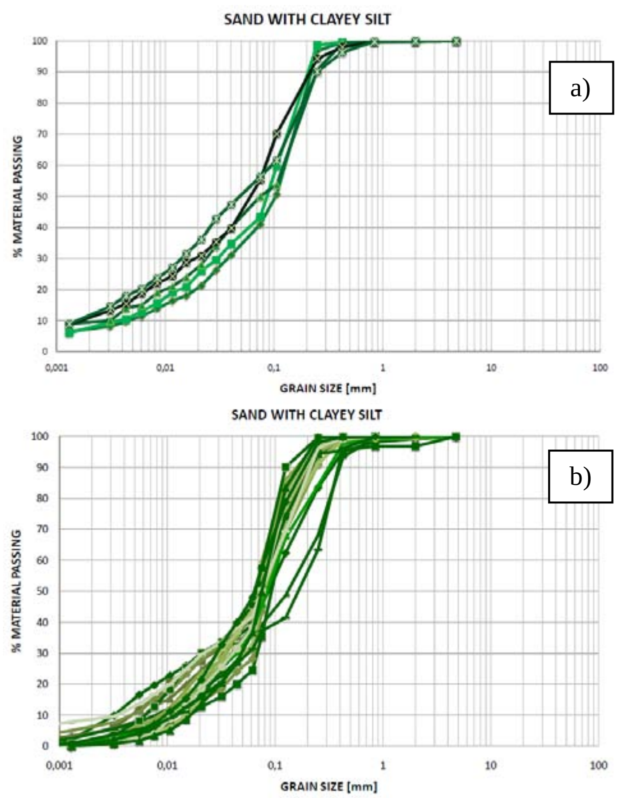

Fig. 9. Grain size distribution curves: sand with clayey silt.
a) District of Lucca; b) District of Pisa.

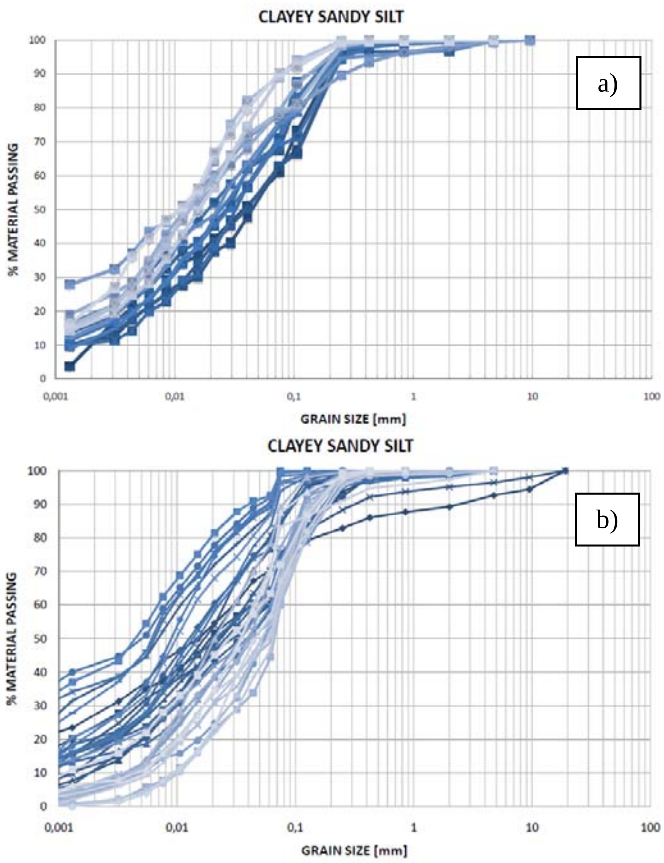

Fig. 10. Grain size distribution curves: clayey sandy silt. a) District of Lucca; b) District of Pisa.

THE GEOTECHNICAL MODEL

Table 5 summarizes the characteristic parameters for the soil groups as obtained from laboratory and in situ testing. The stratigraphic and geotechnical model were used for the analyses described in a companion paper. The third part of Table 5 concerns the 3 km of embankment in proximity of the December 2009 failures (Lucca District).

Table 5 Soil Parameters as deduced by in situ and laboratory test.

LUCCA District	γ_m [kN/m^3]	φ' (°)	c' (kPa)	K (m/s)
Clayey Sandy Silt	18,8	33	0	4,49E-06
Silty Clayey Sand	18,2	33	0	3,50E-06
Silty Sand	17,7	33	0	3,99E-06
Sand	19,6	35	0	4,95E-06
Coarse Sand / Gravel	19,2	35	0	7,54E-06

PISA District	γ_m [kN/m^3]	φ' (°)	c' (kPa)	K (m/s)
Clayey Sandy Silt	18,3	33	0	2,50E-04
Silty Clayey Sand	17,6	32	0	8,25E-05
Silty Sand	16,5	32	0	5,84E-05
Sand	16,5	34	0	7,62E-05

Table 5 Soil Parameters as deduced by in situ and laboratory test.

LUCCA District (Failure areas)	γ_m [kN/m^3]	φ' (°)	c' (kPa)	K (m/s)
Silty Clayey Sand	12,8	32	0	4,25E-07
Silty Sand	12,3	34	0	1,74E-06
Sand	17,7	38	0	1,00E-05

As for the volume weight it is worthwhile to observe that very different values have been measured considering the Shelby samples and continuous samples retrieved from the embankment in the Lucca District near the failure areas. The Shelby samples gave values of the volume weight in between 19.1 - 19.6 kN/m^3. On the contrary, for the continuous samples the volume weight ranged in between 12.3 and 12.8 kN/m^3. The Relative Density inferred from CPTs, carried out in the same areas, according to the Jamiolkowski et al. (1985) method, was as low as 10 %. Therefore, the volume weight inferred from Continuous sampling was considered more realistic. Figure 15 shows the optimum dry volume weight of the soil under consideration as obtained from Standard Proctor test and is compared against those inferred from continuous samples. The comparison is coherent with the low densities obtained from CPTs, on the contrary the dry volume weight inferred from Shelby samples (not reported in the Figure) are quite close to the optimum Proctor value. In addition triaxial compression tests (CIU) carried out on specimens from Shelby samples (not shown in this paper) exhibited a clear dilatant behaviour.

The reason why Shelby samples gave very high values of the volume weight is probably a consequence of the compression of very loose cohesionless soil inside the tube sample during pushing. The areas close to the failures were firstly investigated. After that, Shelby samples were no more used being replaced with Osterberg samples.

The coefficient of uniformity obtained from grain size distribution curves (Figures 7 to 10) was never lower than 7.0 for samples retrieved in the Lucca district and never lower than 5 for those of the Pisa district (closer to the sea). Apart the minimum values, generally the Uc was very high (about 30).

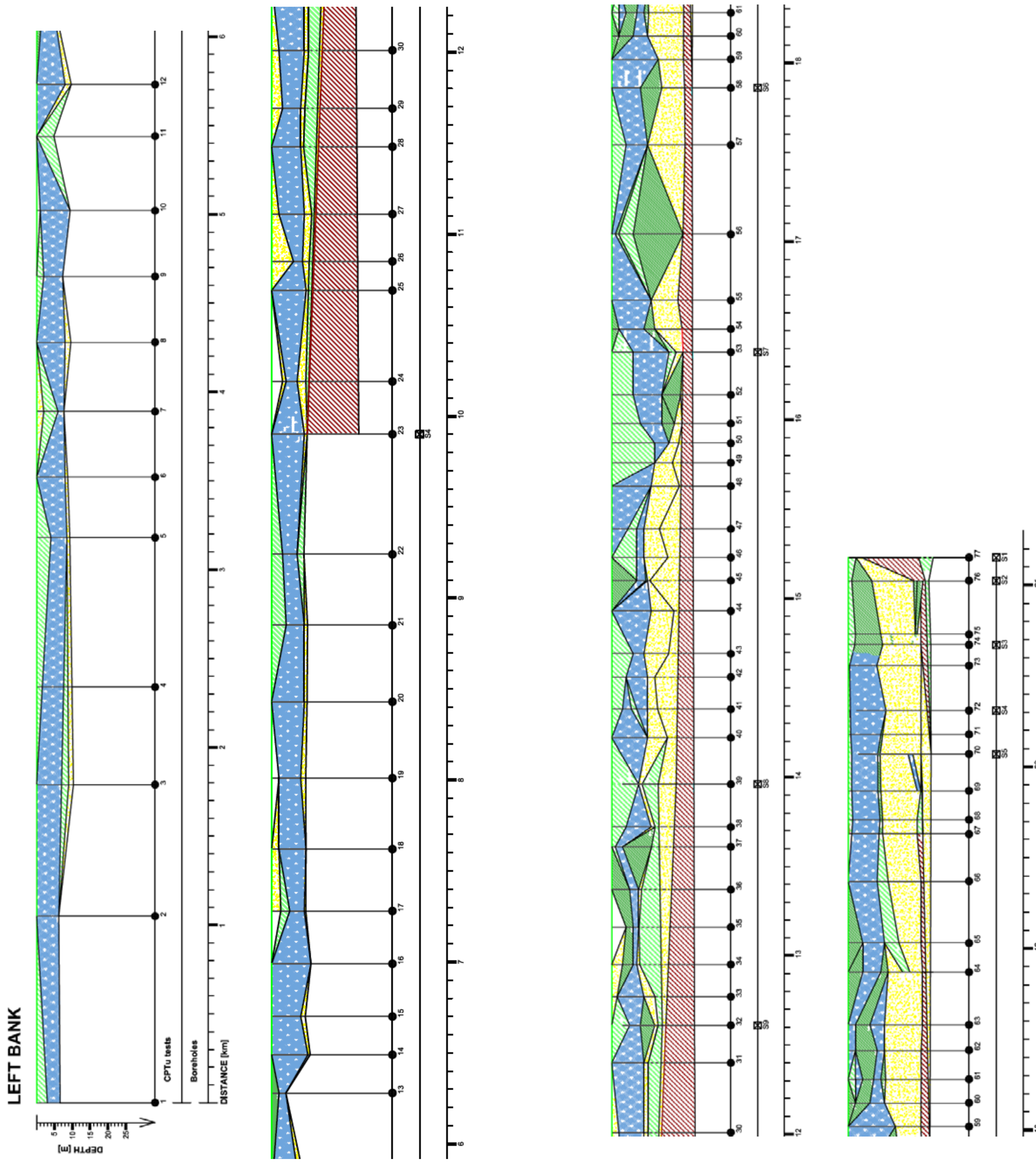

Fig. 11. Stratigraphic model: District of Lucca, left bank (Label: blue = clayey sandy silt; yellow = sand; light green = silty sand; dark green = sand with clayey silt; brown = gravel and coarse sand.)

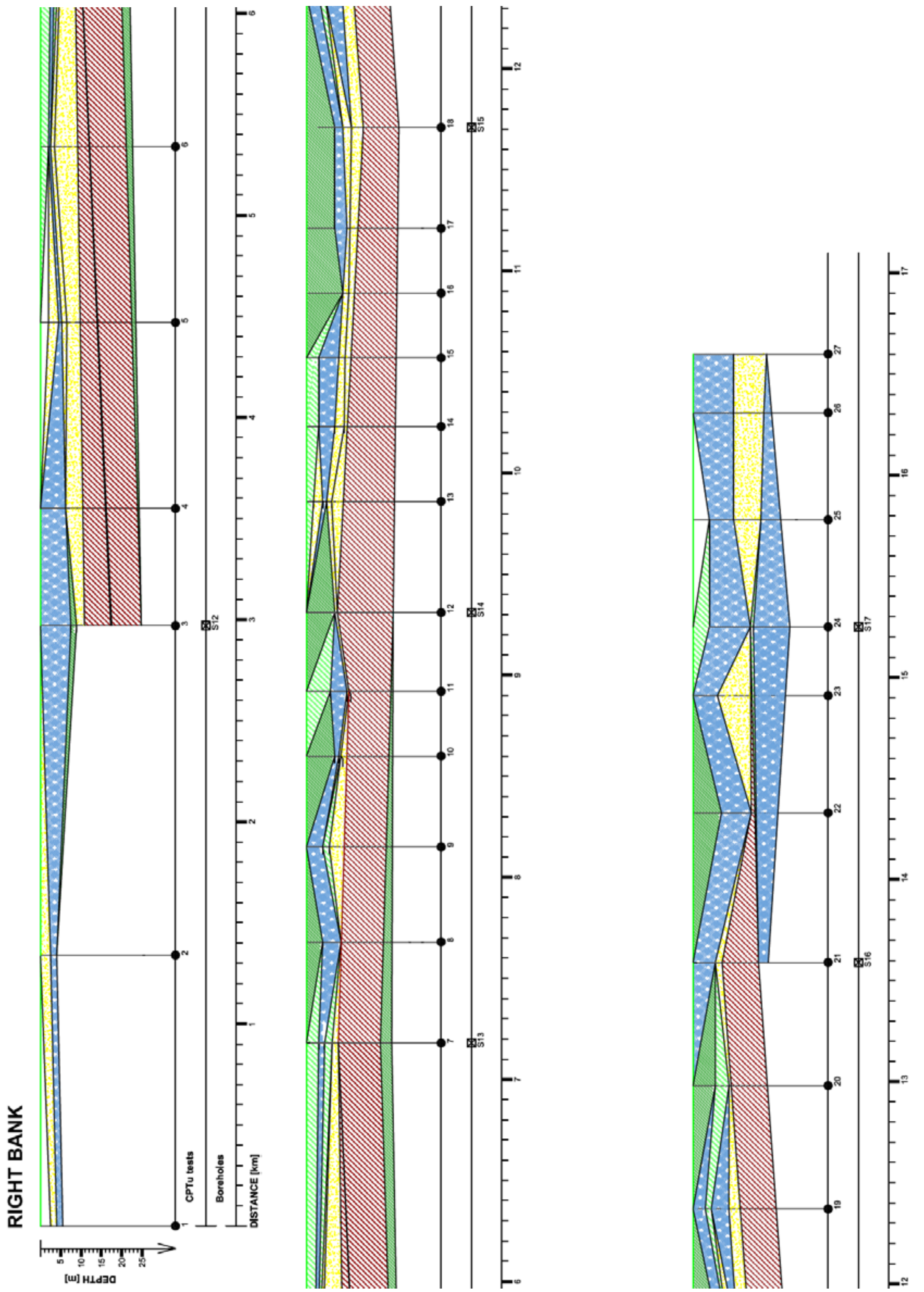

Fig. 12. Stratigraphic model: District of Lucca, right bank (Label: blue = clayey sandy silt; yellow = sand; light green = silty sand; dark green = sand with clayey silt; brown = gravel and coarse sand.)

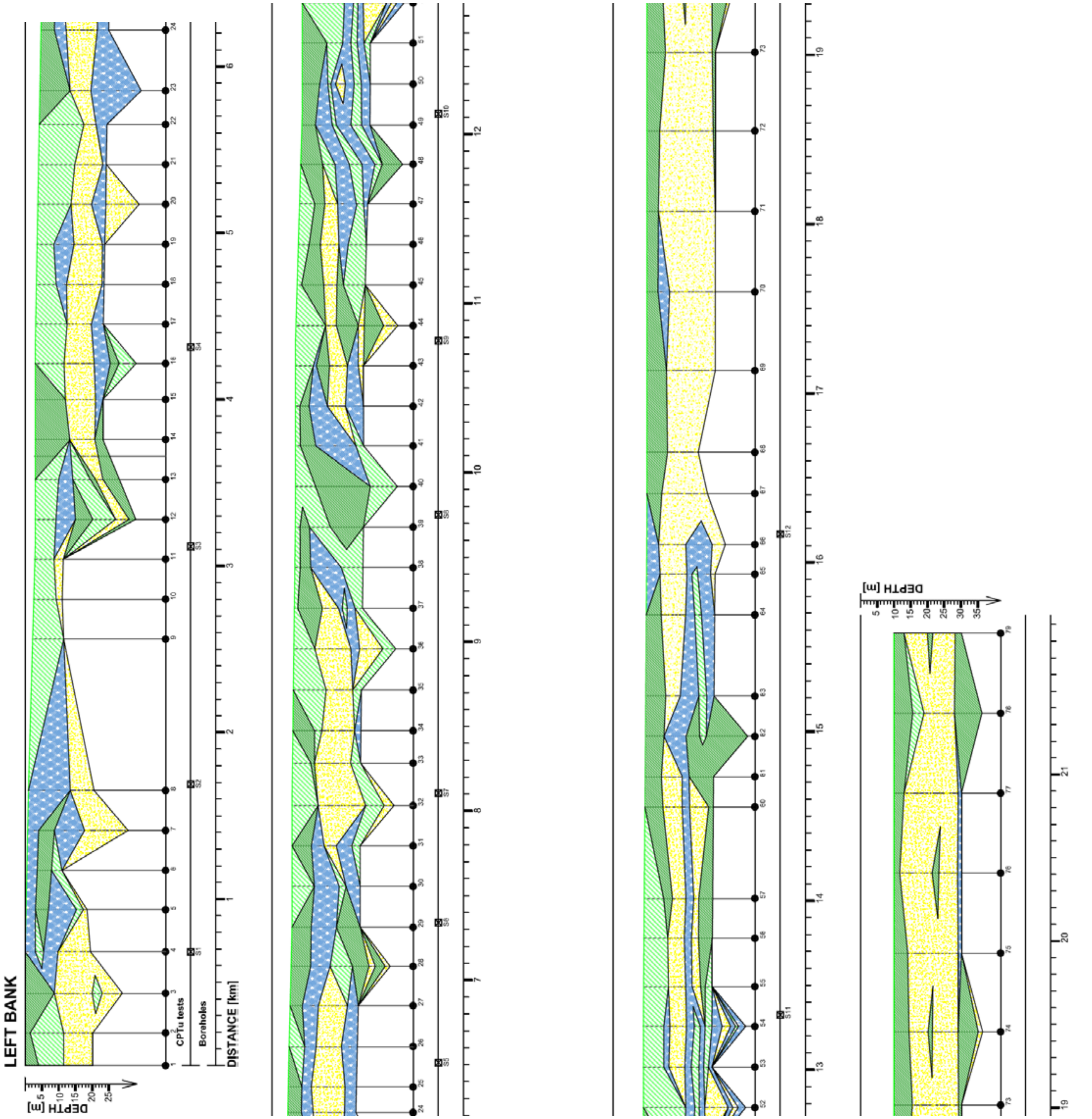

Fig. 13. Stratigraphic model: District of Pisa, left bank (Label: blue = clayey sandy silt; yellow = sand; light green = silty sand; dark green = sand with clayey silt; brown = gravel and coarse sand.)

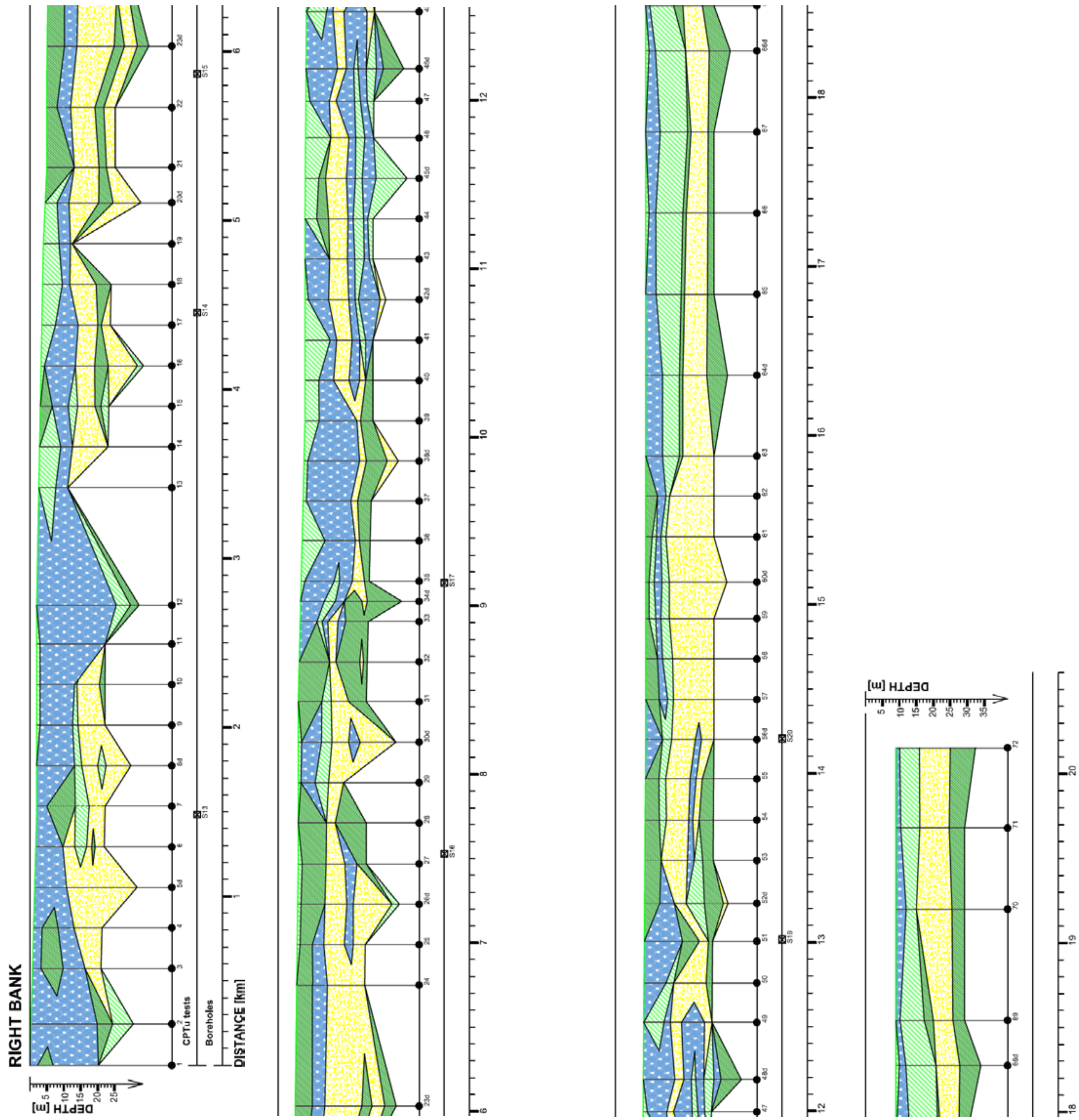

Fig. 14. Stratigraphic model: District of Pisa, right bank (Label: blue = clayey sandy silt; yellow = sand; light green = silty sand; dark green = sand with clayey silt; brown = gravel and coarse sand.)

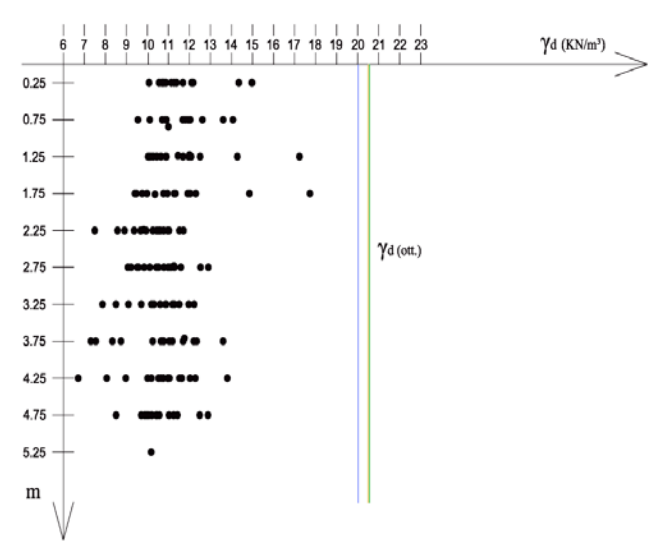

Fig. 15. Comparison between measured γ_d (continuous samples) and $\gamma_{d,opt}$. from Standard Proctor tests.

The values of permeability measured in situ by means of Lefranc tests carried out inside boreholes are summarised in Figures 16a and 16b.

Strength parameters have been obtained from both laboratory and in situ tests. Figure 17 shows the strength envelopes as obtained for various soil types (Table 5) from CIU Triaxial Compression Tests. More specifically, Figure 17.a refers to specimens classified as clayey sandy silt, Figure 17.b refers to sand with clayey silt, Figure 17.c to silty sand and Figure 17.d considers all the data together. Regression analyses of the whole data give a zero intercept and an angle of shear resistance of 33°. The data are for samples from the Pisa district retrieved from the left levee (Fochi 2011). Other data give similar results. Interpretation of CPTs, in the case of "drained" SBT, gives similar values of the angle of shear resistance.

Eventually, Figure 18 shows the comparison of the C_u/σ'_{vo} ratio as inferred from CPTs and the C_u/σ'_{vc} ratio as inferred from laboratory tests plotted vs. depth. The comparison refers to a single borehole and is just an example of the undrained strength for the soil under consideration.

a)

BOREHOLE	IN SITU MEASUREMENTS OF PERMEABILITY (Lefranc tests - District of Lucca)							
	Depth = 165 cm		Depth = 315 cm		Depth = 615 cm		Depth = 915 cm	
	CONSTANT HEAD TEST	FALLING HEAD TEST	CONSTANT HEAD TEST	FALLING HEAD TEST	CONSTANT HEAD TEST	FALLING HEAD TEST	CONSTANT HEAD TEST	FALLING HEAD TEST
	k [cm/s]							
S1	7,24E-04			2,88E-04		1,71E-04		8,74E-04
S2		6,47E-05		3,31E-05		8,23E-04		8,69E-04
S3		2,88E-04		3,87E-04		4,83E-04		1,73E-03
S4		7,91E-05		2,12E-04		1,83E-04		1,01E-03
S6	8,12E-04			7,61E-05	7,06E-05		2,37E-04	
S7	8,85E-04			1,01E-03		3,33E-04	1,51E-04	
S8		9,84E-05		7,02E-05		2,74E-04		7,32E-05
S9		2,61E-04		9,60E-05		1,29E-04	5,46E-05	
S12	2,39E-03		7,35E-04			3,56E-04		1,02E-03
S13	5,33E-04		1,65E-02			9,75E-05	1,50E-03	
S14		5,11E-04		6,64E-04		2,03E-04		6,57E-04
S15		2,78E-04		1,02E-04		1,35E-04		2,75E-05
S16	8,12E-04			9,98E-05		7,19E-04	6,87E-04	
S17		9,12E-05		7,39E-05		8,71E-04		5,38E-04

	SOIL TEXTURE	k [cm/s] MEAN VALUE
	Clayey sandy silt	4,49E-04
	Sand with clayey silt	3,50E-04
	Silty sand	3,99E-04
	Sand	4,95E-04
	Gravel and coarse sand	7,54E-04

b)

IN SITU MEASUREMENTS OF PERMEABILITY (Lefranc tests - District of Pisa)			
FALLING HEAD TESTS			
BOREHOLE	Test	DEPTH [m]	k [cm/s]
S1	S1P1	1,5	6,51E-03
	S1P2	3	2,79E-01
	S1P3	4,5	3,14E-02
	S1P4	8	3,68E-02
	S1P5	13,5	8,61E-03
S2	S2P1	1,5	2,58E-03
	S2P2	3	2,24E-01
	S2P3	4,5	1,57E-02
	S2P4	6,5	2,05E-02
S3	S3P1	1	1,57E-02
	S3P2	2	3,69E-03
	S3P3	3	4,16E-02
	S3P4	6,5	4,36E-02
	S3P5	17	2,71E-03
S4	S4P1	2,5	5,32E-04
	S4P2	4	3,86E-04
	S4P3	7,5	1,15E-03
	S4P4	13,5	4,19E-03
	S4P5	19	2,21E-03
S5	S5P1	2	9,69E-04
	S5P2	3	6,76E-04
	S5P3	6,5	1,85E-03
	S5P4	13,5	6,88E-03
S6	S6P1	1,5	3,93E-03
	S6P2	3	6,12E-03
	S6P3	4,5	3,63E-03
	S6P4	6,5	3,86E-03
	S6P5	15,5	2,05E-03
S7	S7P1	2	3,68E-03
	S7P2	3	8,43E-03
	S7P3	4,5	1,56E-02
	S7P4	6,5	2,29E-02
	S7P5	13,5	7,69E-03
S8	S8P1	1	9,55E-03
	S8P2	3	8,89E-03
	S8P3	4,5	6,58E-03
	S8P4	7,5	7,03E-03
	S8P5	17,5	3,65E-03
S9	S9P1	2,5	5,72E-03
	S9P2	4	8,20E-03
	S9P3	7,5	2,55E-03
	S9P4	14,5	7,12E-03
S10	S10P1	1,5	1,20E-02
	S10P2	4	1,19E-02
	S10P3	6,5	3,51E-03
	S10P4	9,5	5,26E-03
	S10P5	12,5	4,72E-04
	S10P6	15,5	2,05E-03
	S10P7	24	1,09E-03
	S10P8	28,5	6,51E-04
S11	S11P1	3	6,40E-03
	S11P2	4	8,27E-03
	S11P3	6,5	8,39E-03
	S11P4	10,5	1,15E-02
	S11P5	15	3,32E-03
S12	S12P1	2,5	7,26E-03
	S12P2	4	1,01E-02
	S12P3	6,5	2,32E-03
	S12P4	8,5	1,04E-02
	S12P5	10,5	1,64E-03
	S12P6	15,5	8,67E-04
	S12P7	20,5	1,16E-03
	S12P8	25,5	8,99E-04
	S12P9	30	1,44E-03
S13dx	S13P1	2,5	7,12E-03
	S13P2	4	1,22E-02
	S13P3	6,5	1,26E-02
	S13P4	10,5	5,18E-03
S14	S14P1	1,5	9,49E-03
	S14P2	3	9,46E-03
	S14P3	4,5	8,59E-03
	S14P4	8,5	1,06E-02
S15	S15P1	1,5	1,52E-02
	S15P2	3	3,56E-02
	S15P3	4,5	8,52E-02
	S15P4	9,5	7,06E-03
S16	S16P1	1,5	5,14E-03
	S16P2	3	5,57E-03
	S16P3	4,5	1,19E-01
	S16P5	9,5	9,04E-03

	SOIL TEXTURE	k [cm/s] MEAN VALUE
	Clayey sandy silt	2,50E-02
	Sand with clayey silt	8,25E-03
	Silty sand	5,84E-03
	Sand	7,62E-03

Fig. 16. In situ measurements of permeability: a) District of Lucca, b) District of Pisa.

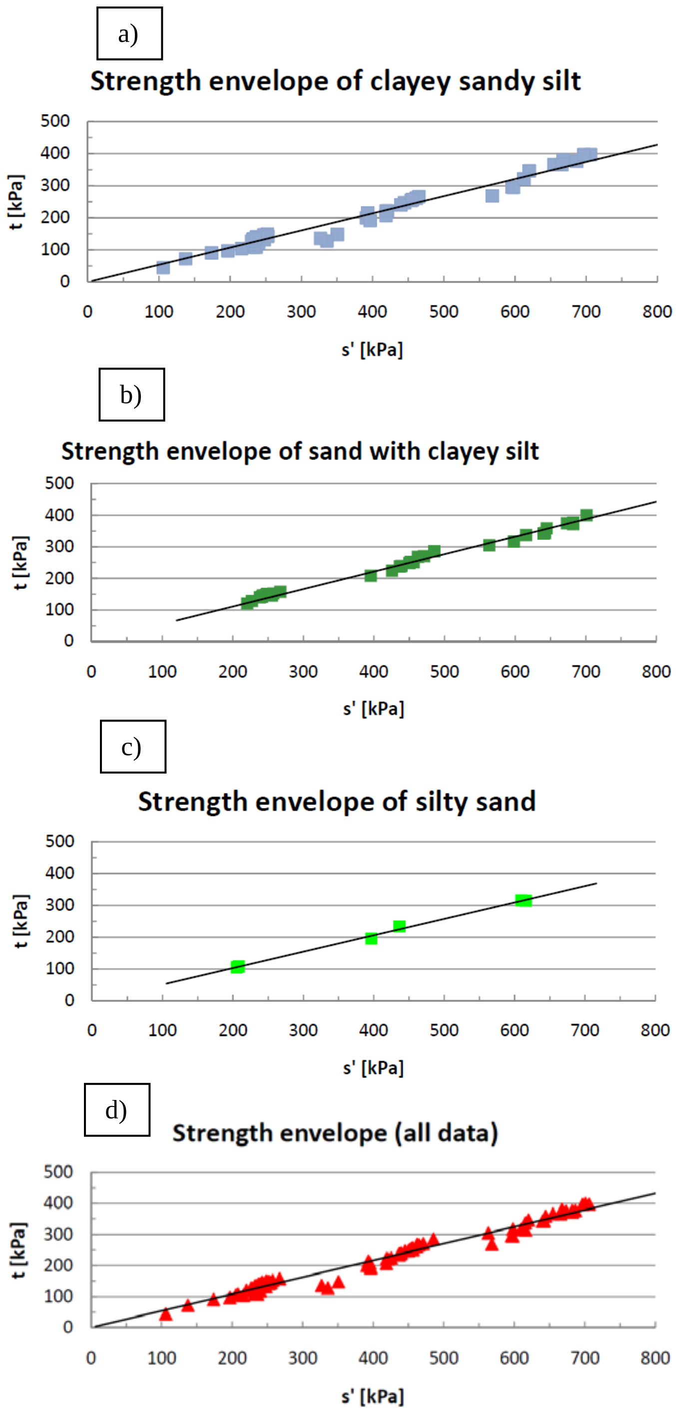

Fig. 17. Strength envelopes as obtained for various soil types (Table 5).

It is possible to make some final comments on the data summarized in Table 5 observing that, nonetheless the differences in terms of grain size distributions both strength parameters and permeability are very similar. More specifically the strength parameters are quite low and the permeability is mainly in the range 10^{-5} – 10^{-6} m/s (i.e. rather permeable soils). In addition, very low densities have been found as far as the embankment in the proximity of the December 2009 failures is considered (about 3 km). Therefore it is possible to conclude that both the embankment and the subsoil have poor to very poor characteristics.

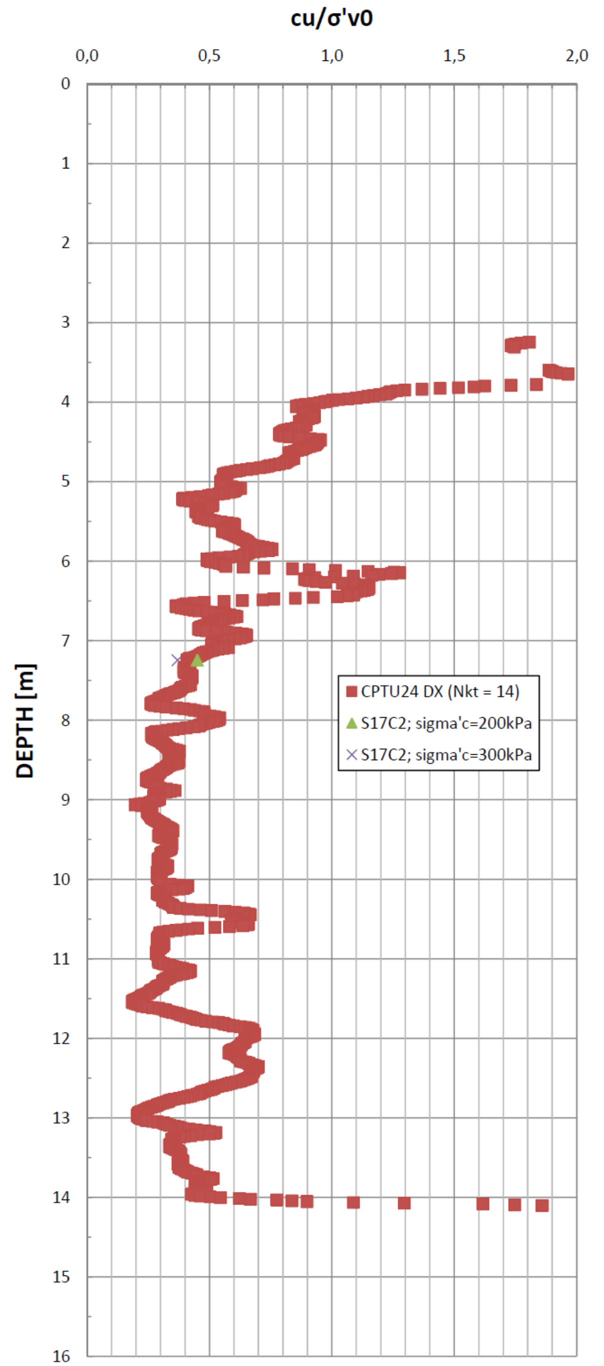

Fig. 18. Comparison of the C_u/σ'_{vo} ratio as inferred from CPTs and the C_u/σ'_{vc} ratio as inferred from laboratory tests plotted vs. depth.

CONCLUSIONS

The present paper describes the investigations carried out to explain two river embankment failures occurred in 2009. River embankments have been erected since the XVIII century and some refurbishment has been applied after flood events. Since no information were available about the river embankments, Local Authorities appointed the Dept. of Civil Engineering of University of Pisa to coordinate and partially execute a comprehensive soil investigation.
The described experience led to the following general considerations:

- Use of ERT is strongly influenced by water content. As a consequence there were a great uncertainty about soil type;
- Sampling in very loose material is a delicate operation which can lead to wrong estimation of mechanical and physical parameters;
- Use of CPT test is suitable for cost effectiveness purposes but calibration of SBT is necessary.
- Use of AF sampler was resolutive to determination of physical properties of soil

In addition, it is worthwhile to point out the costs of the investigation campaigns:

- 60000,00 euros for the 3 km of embankments in proximity of the December 2009 failures
- 390000,00 euros for another 24 km

The above costs include those for test interpretation and Geotecnichal Consultancy.

ACKNOWLEDGEMENTS

The Authors would like to thank the District of Lucca and the District of Pisa (Ufficio Difesa del Suolo) for making available the data reported in the present paper.

REFERENCES

Autorità di Bacino del Fiume Serchio [2010]. *"REPORT sull'evento alluvionale registrato nei giorni 24-25 dic. 2009 nel Bacino del Fiume Serchio". Report 29/01/2010*

Barba D. [2011]. *"Identificazione del profilo stratigrafico mediante prove penetrometriche statiche CPTu"*. First level degree thesis.

Fochi F. [2011]. *"Analisi di stabilita' degli argini del fiume serchio nella Provincia di Pisa"*. Master degree thesis.

Geologismiki [2009]. *"CPeT-IT User's Manual v.1.3"*. http://www.geologismiki.gr/Documents/CPeT-IT/HTML/index.html

Ghini M. [2010]. *"Caratterizzazione geotecnica di un rilevato arginale"*. First level degree thesis.

Jamiolkowski, M., Ladd, C.C., Germaine, J.T. & Lancellotta, R., [1985]. *New Developments in Field and Laboratory Testing of Soils*. Theme Lecture, Proc. XI ICSMFE, San Francisco, CA.

Pierotti A. [2011]. *"Analisi di stabilita' degli argini del fiume Serchio in Provincia di Lucca"*. Master degree thesis.

Principe C., Malfatti A., Rosi M., Ambrosio M. Fagioli M.T. [1997]. *Metodologia innovativa di carotaggio microstratigrafico: esempio di applicazione alla tefrostratigrafia di prodotti vulcanici distali.* Geologia Tecnica Ambientale Vol 39, 4/97.

Schmertmann J.H. [1978]. *Guidelines for cone penetration test performance and design*. US Dept. of Transportation, FHWA, R.78-209. Washington D.C.

So.Ge.T s.n.c. [2011]. *Internal report.*

TomoLAB [2009]. *TomoLAB User Manual. Geostudi Astier srl. Livorno, Italy.* www.geoastier.com

Vannucci S. [2011]. *"Il ruolo delle indagini geoelettriche nelle verifiche degli argini fluviali"*. First level degree thesis.