Engineering geological mapping for urban areas of the Oltrepo Pavese plain (Northern Italy)

CLAUDIA MEISINA[1]

[1] *Department of Earth Sciences, University of Pavia. (e-mail: cmeisina@manhattan.unipv.it)*

Abstract: The objective of the study was to develop a methodology for engineering geological mapping to support urban planning and development. The study area is located in the province of Pavia and corresponds to the Southern and Central sector of the Po River Plain (Northern Italy). It has an extent of about 440 km^2 and several important urban areas are located there. Geomorphologically, fluvial terraces and piedmont fans characterise the area. The recent river deposits consist mainly of coarse-grained units (sand, pebbles, gravel). The upper part of the older alluvial deposits are strongly weathered and composed of a large amount of clay.

The adopted approach was multidisciplinary, such that data regarding the geology, geomorphology, hydrographic network, urban development and history of the towns were used to develop a geological/geotechnical model of the area. In the first step the landforms (alluvial terraces, alluvial fans, etc.) were mapped from aerial photographs. In the second step, for each landform the nature of surface materials (lithostratigraphic, hydrogeological and geotechnical characteristics) was determined. The datasets included boreholes and trial pits. Collection of penetrometer results (DCPT, SPT and CPT), calibrated against soil profile logs, helped with the geotechnical characterisation of the soils. Geotechnical and lithological profiles were then constructed.

Engineering geological zoning was carried out by assessing three attribute groups: lithologies, geometries, and geotechnical characteristics. The resulting engineering geological units (areas that may be regarded as homogeneous from the geomorphological and engineering geological point of view) are useful for studies concerning geohazard susceptibility and foundation conditions.

Résumé: L'objectif de l'étude est la mise au point d'une méthodologie pour la cartographie géotechnique à support d de l'aménagement du territoire. La zone étudiée est localisée dans la Province de Pavia et corresponds au secteur central et méridional de la Plaine du Fleuve Po (Italie du Nord). Le territoire a une surface d'environ 440 km^2 avec plusieurs centres urbains. La géomorphologie est caractérisée par des terrasses alluviales et des cones de déjections. Les dépots alluviaux récents sont constitués par des matériaux grossiers (sable, gravier). La partie supérieure des dépôts plus anciens est très altérée est composée par de l'argile. La méthode utilisée a une approche multidisciplinaire et elle prend en considération la géologie, la géomorphologie, l'hydrographie, et l'histoire des villes au but du développement d'un model géologique et géotechnique du territoire. Dans un premier niveau les formes du paysage ont été cartographiées parmi les photographies aériennes. Dans un deuxième niveau on a déterminé les caractéristiques lithologiques, hydrogéologiques et géotechniques de chaque forme. La base donnée comprend les sondages, les forages d'eau et les essais géotechniques. Les données penétrometriques, calibrées parmi les sondages, ont permis la caractérisation géotechnique des sols. Des profils géotechniques et lithologiques on été construis. Le zonage géotechnique a été réalisé parmi 3 critères : la lithologie, la géométrie des couches du sol et les propriétés mécaniques. On a obtenu des unités géotechniques (unités homogènes du point de vu géomorphologique et géotechnique), qui peuvent être utilisées pour des études d'aléa ou de l'aptitude des sols à la construction.

Keywords: engineering geology maps, foundations, urban geology, geohazard, penetration test, mechanical properties.

INTRODUCTION

The purpose of engineering geological mapping is to provide information about characteristics of the territory for planning, land use and engineering structures. In recent years information about ground conditions of urban environment has assumed increasing importance, confirmed by problems resulting from unfavourable engineering geological conditions (swelling/shrinking soils, collapsible soils, etc). Several authors have thus developed methods about engineering geological mapping in urban areas (Anon. 1976, De Mulder 1988, Anon 1991, van Rooy & Stiff 2001, Zuquette *et al*. 2003, Culshaw 2005). In this context, the properties of man-made deposits derived by anthropogenic processes also need to be defined (Rosenbaum *et al*. 2003). Engineering geological mapping requires the identification, delineation and characterisation of engineering geological units on the basis of attributes related to soils, relief, and groundwater. These units are then analysed to identify natural and anthropogenic hazards and determine the condition of foundations.

The aim of the present study has been to develop a methodology for engineering geological mapping to support urban planning and development in the Oltrepo Pavese area of northern Italy, with particular attention to characterising basic engineering geological units.

THE STUDY AREA

The study area is situated in the Northern Apennine fringe, in the province of Pavia. It corresponds to the Southern and Central sectors of the Po River Plain, covering about 440 km^2. The most important towns are Voghera (40,000 inhabitants), Broni, Stradella and Casteggio.

The Quaternary cover of the Po River Plain consists of alternating impermeable sediments (silt and clay) and more permeable horizons (gravels belonging to the Apennine alluvial fans, and sandy clays generated by interaction of the Po River sediments with the Apennine ones). A shallow phreatic aquifer and various deep aquifers of both phreatic and confined type were distinguished.

The configuration of the aquifers is affected by deep tectonic structures developed in the Tertiary. The neotectonic movements have accentuated the positive structures and depressed the negative ones, thus controlling the thickness of the superimposed continental sedimentary cover and influencing the underground hydrogeology (Braga & Cerro 1988).

The Quaternary sediment thickness decreases from west to east; minimum thickness and outcrop of the marine substratum corresponds to the Stradella thrust.

Geomorphologically, fluvial terraces and piedmont alluvial fans characterise this zone. The alluvial deposits could be classified into three major types (Figure 1). The actual and recent river deposits consist mainly of coarse grained units. All along the piedmont margin, which separates the first foothills of the Apennines from the alluvial deposits of the Po plain, three orders of pre-Wurm fluvial terraced deposits are present. The upper part of the older alluvial deposits is strongly weathered and includes a large amount of clay. The alluvial deposits of the Main Level of the Po Plain are very heterogeneous.

Weathered aeolian deposits (loess) form thin sheets that cover the flat parts of the oldest terraces; most of the loess has been reworked to form a variable cover of loessic colluvium.

These deposits form the foundation soils beneath the urban areas of the region. In the most important urban areas the natural deposits are overlain by considerable deposits of made ground.

The climate of Oltrepo Pavese has an average annual rainfall of around 700 mm.

The geological, structural and geomorphological characteristics make the Oltrepo Pavese particularly vulnerable to hydrogeological hazards, shrink/swell of the clay soils, and subsidence. Most engineering problems are related to single storey family homes. Such buildings are generally founded on simple shallow concrete strip footings, which generally extend to depths of between 1 m and 2 m below ground level. Only the economic losses due to volume change of clay soils have been estimated, at around 20% of the building cost. The material source of expansive/shrinking soils is from the weathering of the alluvial deposits in the Po River Plain (Meisina 2003).

Based on their origin, expansive/shrinking soils in the plain area of Oltrepo Pavese can be divided into two basic types: alluvial soils (IIa and IIb) and aeolian soils (III). Soils of type IIa represent only 4% of swelling/shrinking soils and are found on the oldest alluvial terraces. Soils of type IIb correspond to alluvial deposits of the Main Level of the Po Plain (as grey clays, often in lenses with layers of silt and sand or gravel); they are the most widespread (39%) and very heterogeneous. Type III is colluvium, largely of loess and often weathered, forming thin sheets that cover the flat areas of the oldest terraces.

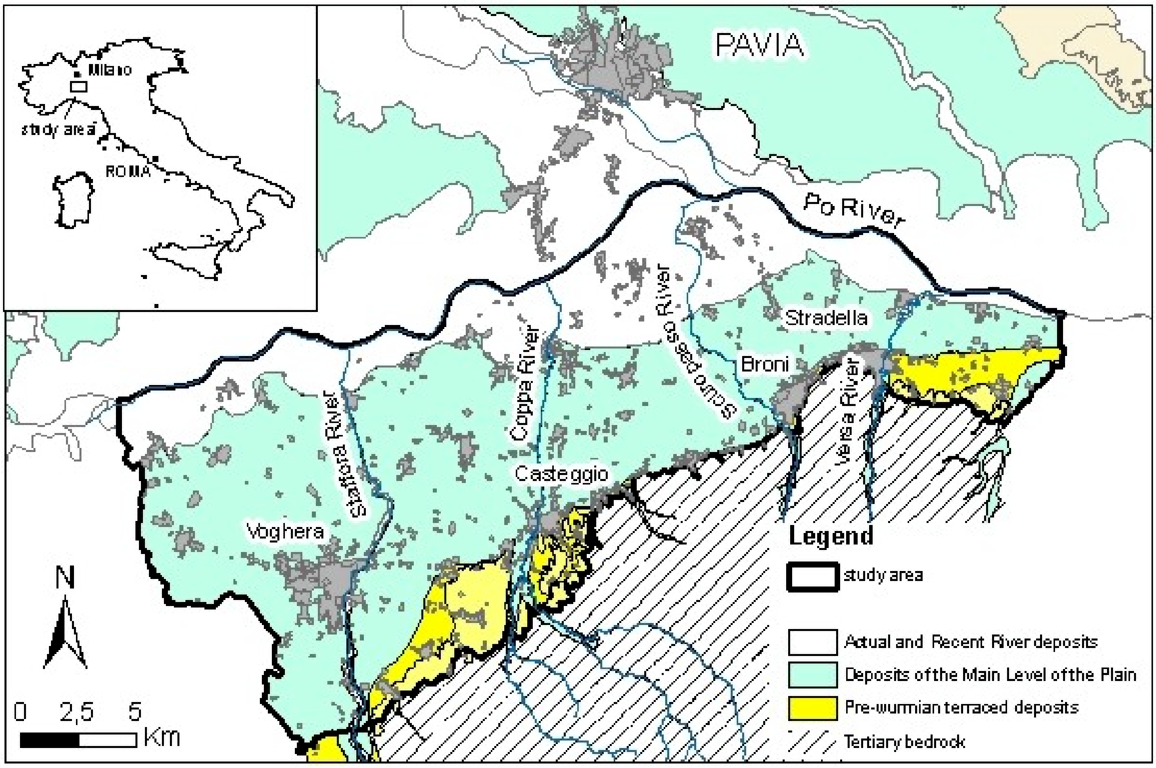

Figure 1. Geological map of the study area

METHODOLOGY

The adopted approach has been multidisciplinary (Figure 2). Data concerning geology, geomorphology, hydrology, urban development and history have been used to construct a geological/geotechnical model of the area.

The first step was to map the landforms (alluvial terraces, alluvial fans, etc.) from aerial photographs.

In the second step, for each landform the nature of the surface materials (lithostratigraphic and hydrogeological characteristics) was determined. The following criteria have been used for discrimination of engineering geological mapping units:

- Lithology
- Geometry (thickness of the different soils, spatial relation between the strata, etc..)
- Geotechnical behaviour.

The geological and hydrogeological data were collected from the public administration (municipal, provincial) or from site investigation reports. The datasets included 218 boreholes, 20 trial pits and 235 water well records. The site investigations are distributed non-uniformly within the urban areas and along the highways; they range in depth from 5 to 50 m and in some cases (the eastern sector) penetrate the Tertiary bedrock.

A geological and geotechnical GIS containing the site investigation data was then created. The data were processed and analysed in terms of quality, which was generally poor for the water well records. The borehole logs had been compiled in detail. These required simplification: 13 dominant lithologies were identified (clay, silty clay, sandy clay, gravel, sandy gravel, gravel and clay, silt, clay silt, sandy silt, sand, clay sand, gravely sand, silty sand). Based on these subdivisions the boreholes, water well and trench pit records were correlated.

The logging of the cores has highlighted the vertical and lateral variability of the lithologies. Several areas were thus identified as being homogeneous from a geomorphological/lithological point of view; for each, a representative lithological profile could be constructed showing the stratigraphical sequence and boundaries of the various strata.

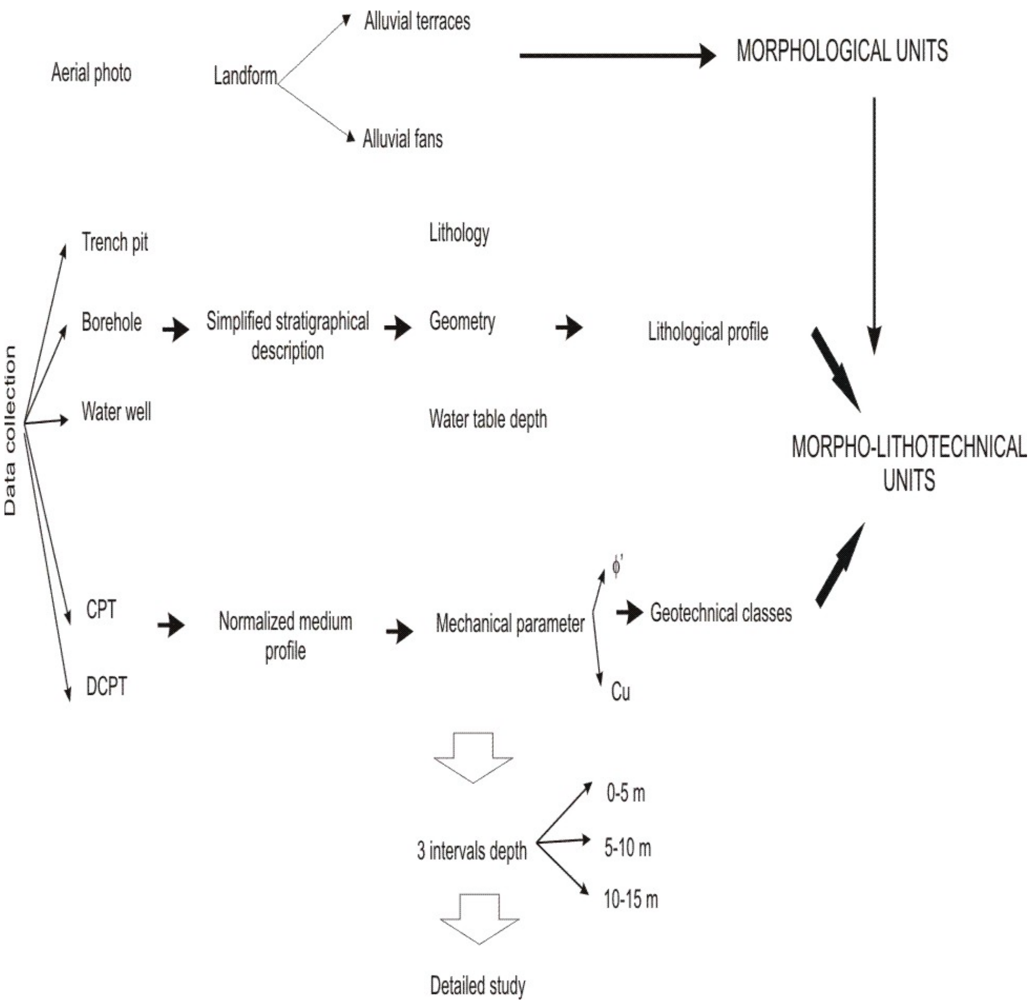

Figure 2. Steps to identify the engineering geological terrain units.

Collection of cone penetrometer test results (176 DCPT, 20 SPT and 266 CPT), calibrated against soil profile logs, aided the geotechnical characterisation of the soils. The data were statistically treated due to the high number of the test results and the wide scatter of their geotechnical properties. For each site the penetrometer data were filtered and an average profile calculated (tip resistance/depth, number of blows/depth). The standard deviation indicated the variability. From the average profile and for each engineering geological unit, the following geotechnical parameters could be derived: the angle of internal friction ϕ' for non-cohesive soils (De Mello 1971), and the undrained shear strength c_u for the cohesive soils. On the basis of these strength parameters, each engineering geological unit was characterised from a geotechnical point of view (into six horizons for non-cohesive soils (from I1 to I6) and into 4 horizons for cohesive soils (from C1 to C4)) (Table 1).

Table 1. Summary of geotechnical parameters for the six geotechnical horizons.

Non-cohesive soils	ϕ'	Cohesive soils	Cu (kPa)
I1	< 25	C1	< 50
I2	25-30	C2	50-100
I3	30-35	C3	100-150
I4	35-40	C4	>150
I5	40-45		
I6	>45		

Zoning the area on the basis of the geotechnical horizons provides a basis for planning foundations and planning appropriate geotechnical testing programmes in order to define the local situation in detail. Three depth intervals for each engineering geological unit were considered:

- 0 to 5 m (corresponding to the subsoil of shallow foundations)
- 5 to 10 m
- 10 to 15 m (corresponds to the subsoil of deep foundations).

Building damage was recorded in the database along with data collected from walk-over surveys and historical documents. The engineering geological units were mapped at a scale 1:50,000.

The third step was to study in detail the worst engineering geological units, at 1:5,000 scale. Artificial deposits were also classified and mapped. This mapping gave sufficiently detailed and quantitative information concerning the zonation and engineering behaviour of the foundation soils.

ENGINEERING GEOLOGICAL MAPPING AT A LARGE SCALE

Geomorphologically, three units were identified: the pre-Wurm alluvial deposits, the Main Level of the Po Plain alluvial deposits, and the Active and Recent alluvial deposits.

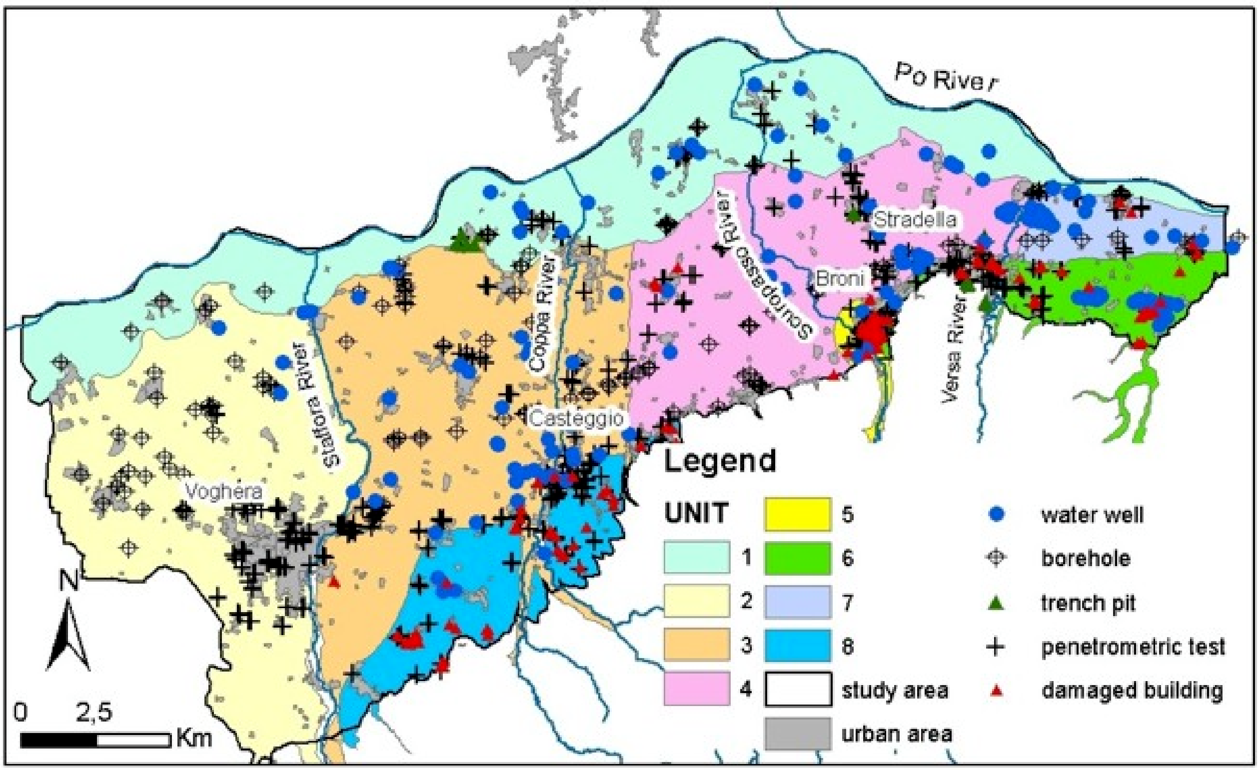

Figure 3. Distribution of engineering geological units.

Characterisation of these landform units in terms of their engineering characteristics utilised the above criteria (Figures 3 and 4), denoting the following:

Unit 1: Active and Recent alluvial deposits of the Po River. Alternating silty sand and gravely sand, medium dense to dense (I3, I4, I5). The depth to the water table is less than 2 m.

Unit 2: Alluvial deposits of the Main Level of the Plain. Firm to stiff clay silt and silty clay (C1, C2, C3) with a thickness ranging from 2 to 8 m overlying dense sand and gravel (I3-I5) with lens of firm to stiff clay silt (C3-C4). The depth to the water table ranges between 4 and 8 m in the northern part to more than 20 m in the southern part (Voghera town).

Unit 3: Alluvial deposits of the Main Level of the Plain. Clay silt and silty clay, very thick (6 to 20 m) (C1-C3), with the highest values in the piedmont margin near the town of Casteggio.

Unit 4: Alluvial deposits of the Main Level of the Plain. Clay silt and silty clay (C2-C3), up to 4 m thick. The clay is generally underlain by layer of sand and gravel (I3-I4). The depth to the water table is 2-4 m.

Unit5: Alluvial fan (Scuropasso River). The soils of this unit are very heterogeneous; comprises clay (C2, C3) with layers of silt and sand or gravel.

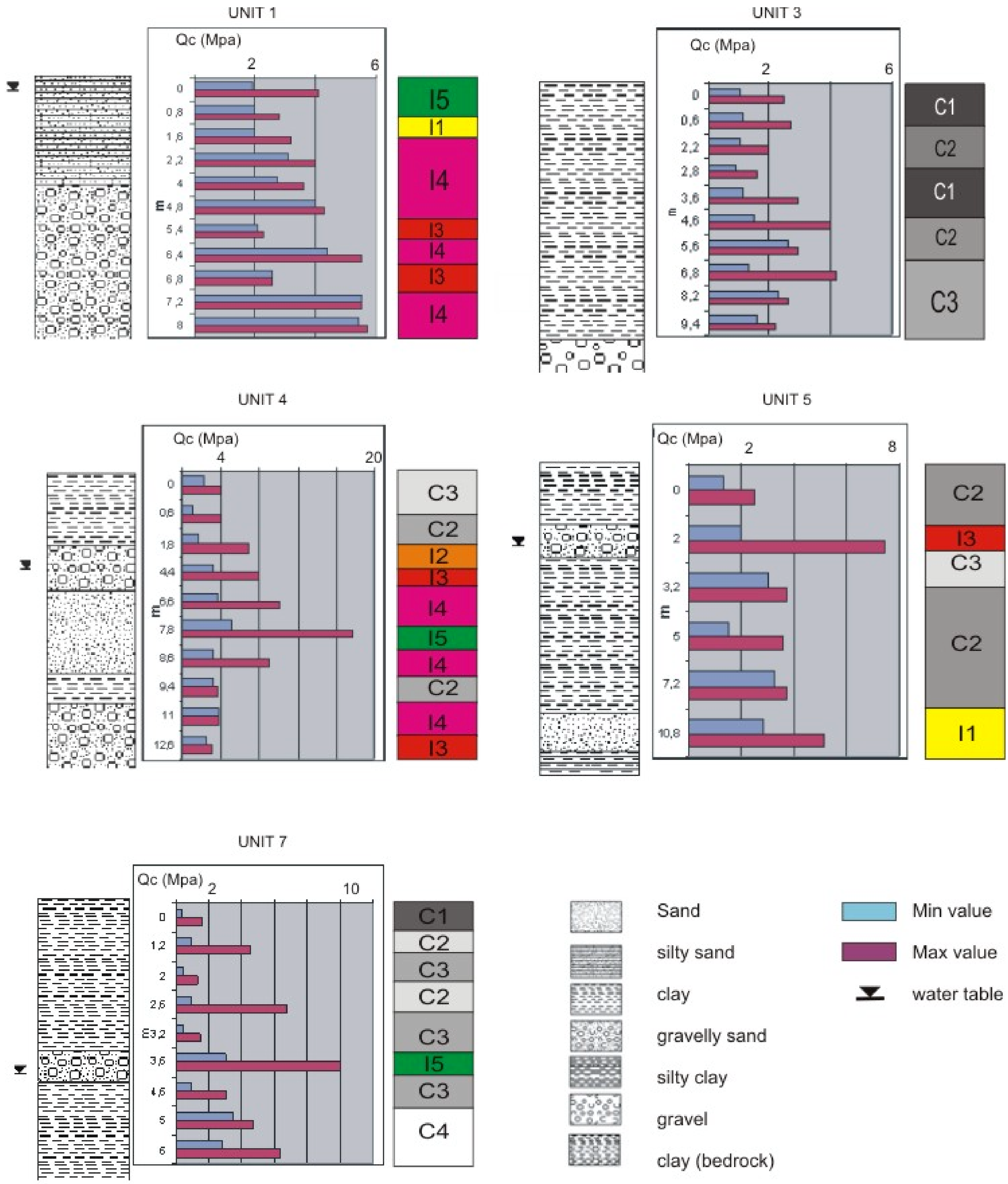

Figure 4. Typical stratigraphical and geotechnical profiles of the different engineering geological units.

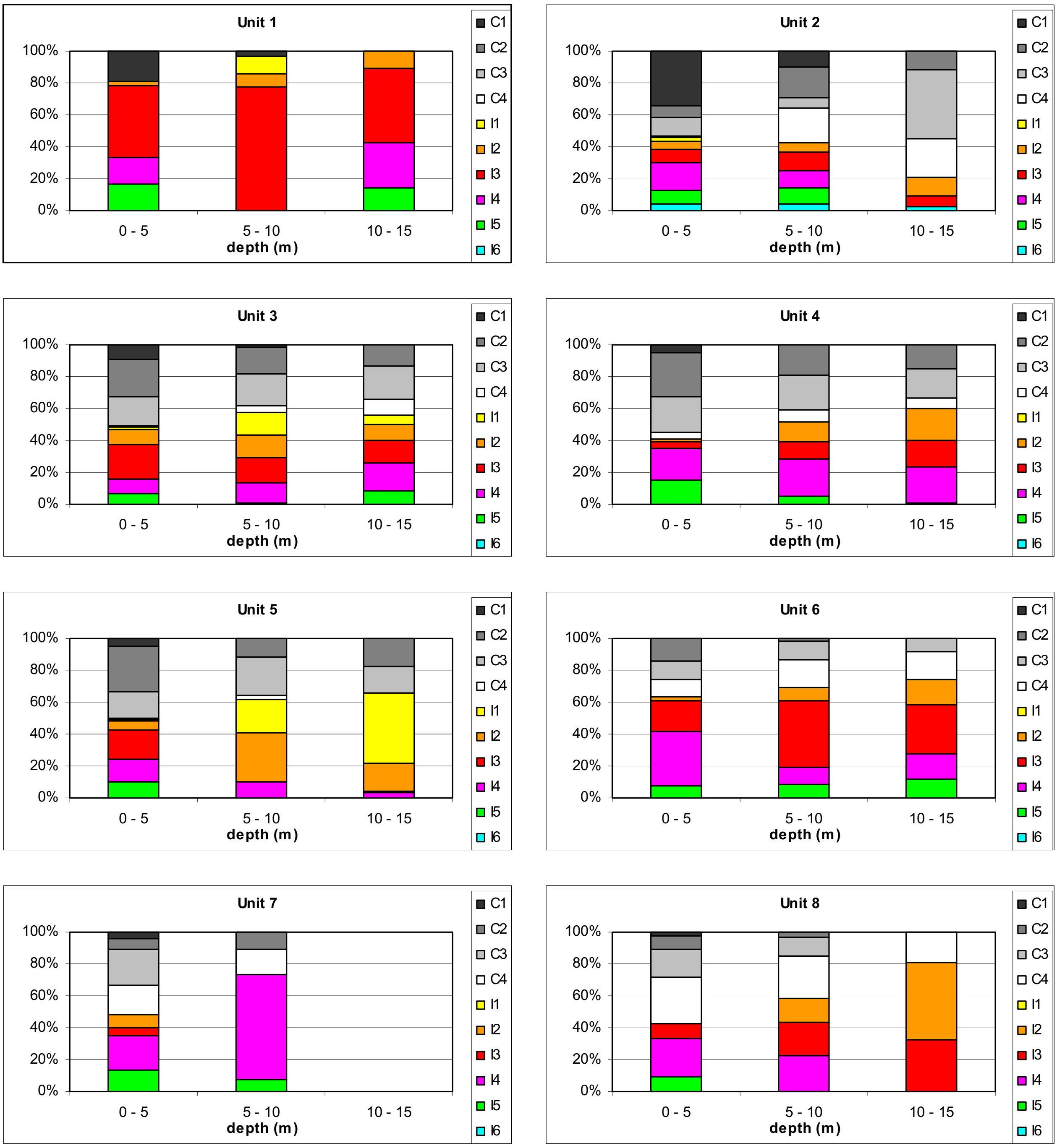

Figure 5. Thickness (%) of the different geotechnical horizons over different depth intervals.

Unit 6: pre-Wurm terraced deposits. Clay and silt interbedded with clay and sand. Sometimes under a cover of loessic colluvium. Locally the oldest alluvial deposits are strongly weathered and contain a large amount of clay.

Unit 7: Alluvial deposits of the Main Level of the Plain. Clay with lens of sand, gravel and silt.

Unit 8: pre-Wurm terrace deposits. Comprising reddish yellow clayey, up to 8 m thick, derived from the weathering of older alluvial sediments. The bottom of the soil mass is a sand and gravel layer (old alluvium). Calcareous and Fe-Mn nodules are often found within the soil mass. The upper clay is stiff to very stiff and generally is fissured (C3-C4); it has a very high swelling-shrinking potential.

In Unit 1, cohesive soils are not present. In Units 2, 3, 4 and 5 cohesive soils prevail (50-60% of the thickness) in the upper (top 5 m) portion of the soil profile (Figure 5). Generally all units show an improvement of their geotechnical properties with depth. Nevertheless, in some cases (Unit 5) stiff cohesive soils overlie very loose non-cohesive soils (I1). In Units 6, 7 and 8 the cohesive soils are predominant only in the top 5 m; thereafter the sub-soil is composed of gravel and sand.

Damaged buildings are found in Units 8 (34%), 6 (29%), 5 (20%) and 4 (9%). Units 8 and 6 correspond to the oldest terraced alluvial deposits, characterised by high clay content. Damage appears to be related to shrinkage beneath foundations during periods of drought. This is confirmed by typical cracking of buildings (where cracks go on widening each dry summer and partially close up during winter) and the very high swelling/shrinkage potential of the soils (a swell strain of up to 40 % was recorded at the Shrinkage Limit). In Unit 6 some damaged buildings are located on clay silt deposits; in this case the cause of the damage is not clear. Houses with problems are generally located around water wells and their damage can be related to subsidence caused by water abstraction. Unit 5 has the highest number of damaged buildings per square kilometre (7.2) and all the houses within are concentrated in the new urban development of Broni town. This was therefore chosen for a detailed study to identify the cause(s) of the damage.

ENGINEERING GEOLOGICAL MAPPING AT A DETAILED SCALE

Detailed studies at a scale of 1:5,000 were concentrated on where lithological and geotechnical properties of the engineering geological units indicated potential for foundation problems. The town of Broni is thus presented, located on the Apennine fringe of the eastern sector of the study area (Figure 1).

Broni is built mainly upon the alluvial fan deposits of the Scuropasso River (Unit 5), which are very heterogeneous and vary both vertically and horizontally over short distances. The south-western sector of the town was selected for urban expansion 20 years ago and many single storey family houses with shallow foundations were built.

Silty clay and clayey silty deposits with high to very high swelling/shrinking potential constitute the first layer. They are soils of type C2, C3 (q_c=1-2 MPa) and their thickness varies from 4 m in the western part to 20 m in the northeastern part (Fig. 6). In the western sector thin lens of silt and sand are interbedded. The underlying layers consist, from top to bottom, of sand and gravel, silty clay, gravel and Tertiary marls.

The alluvial deposits consist of two aquifers interbedded with a discontinuous silty clay aquitard: the groundwater is pumped from the deepest aquifer, which is semi-confined, from a depth of 10 to 25 m. The water table fluctuations during drought periods reach 2.5 to 3 m. The depth of the active zone in the period 1992-2001 was 2.8 m. The moisture regime of soil was also influenced by a seasonal perched water table.

Several buildings (single storey family houses), founded on conventional shallow concrete strip footings (0.5-2.5 m), were recently damaged (Figure 6). Cracks appeared at the end of 1980s (a drought period) with a worsening during 1998-2000 and 2003. Cracking is progressive; cracks generally close up during the wet season in relation with rainfall, and reopen during the following dry season.

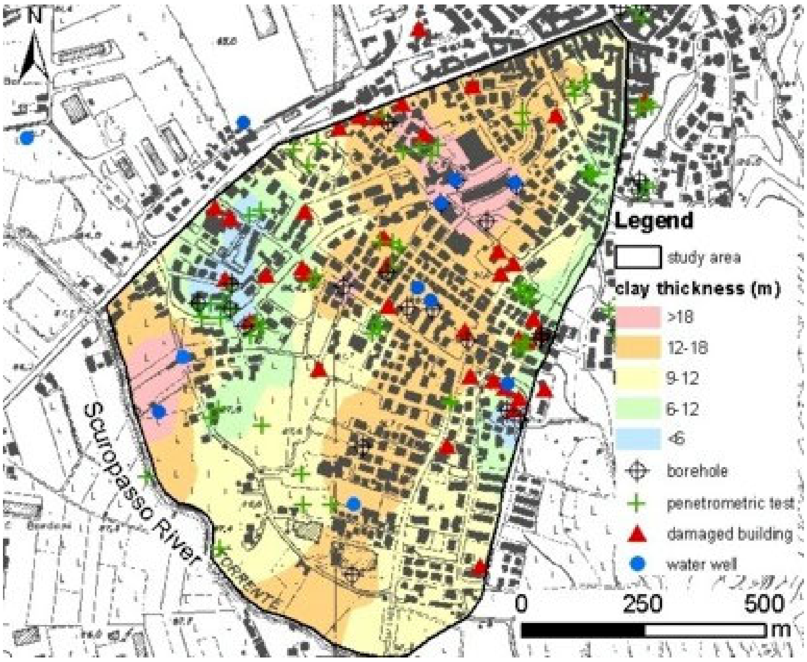

Figure 6. Thickness of clay deposits within the town of Broni.

A series of maps were then prepared at 1:5,000 scale in order to understand the causes of building damage. Engineering geological Unit 5 was thereby subdivided into several homogeneous "shallow sub-units" (Figure 7). These were defined for the shallowest 5 m. Near the Scuropasso River, clay with significant organic content (peat) are present; they correspond to swampy areas. Towards the NE the percentages of sand and silt increase.

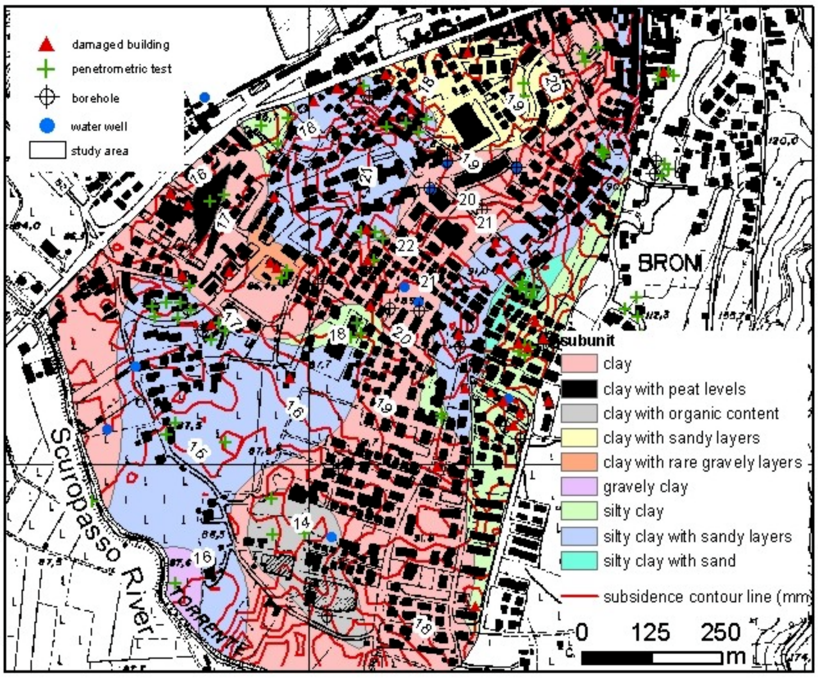

Figure 7. Subdivision of engineering geological Unit 5 (shallowest 5 m) within the town of Broni.

Man-made deposits were also taken into account (Figure 8). These were classified into 6 classes following the approach of Rosenbaum *et al*. (2003):

- Made ground: areas in the south-western sector of the town where the ground was artificially deposited on the natural ground surface (e.g. road embankments). The artificial ground consists of gravel and sand with silt; sometimes brick waste is present;
- Worked ground: very small areas where the ground was artificially cut away (road cutting);
- Infilled and partially infilled ground: areas in the eastern sector where the ground was cut away and then deposited as artificial ground. These have a maximum thickness of 3 m and are composed of waste material derived from construction;
- Landscaped ground: large areas of the town where the original ground surface has been extensively remodelled but where it is difficult to delineate areas of worked (excavated) ground and made ground. The thickness of the artificial ground here ranges between 0.5 and 1 m.

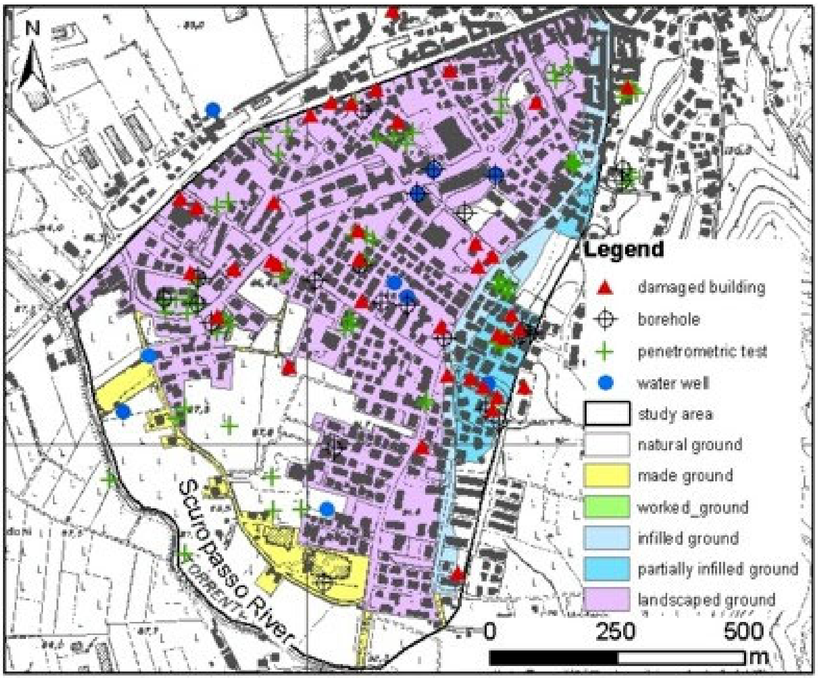

Figure 8. Classification of man-made deposits.

Damaged buildings are located largely on the most heterogeneous sub-units: silty clays with layer of sand (43%) and silty clays (23%). A number of damaged houses have also been built on clays (17%).

The "Permanent Scatterers" (PSs) technique (an algorithm for processing SAR data developed by Politecnico Milano (Ferretti *et al*. 2001)) was applied to detect and monitor ground displacement in the town. The PSs act as a "natural" geodetic network and correspond to buildings. The technique identified vertical ground displacements (settlement) in the northern and eastern parts of Broni, corresponding to the sub-unit "silty clay with layer of sand" and where the clay is very thick. The time series of nonlinear PS shows abrupt variations after May 1998 (Figure 9): a rapid increase of settlement was observed, reaching 14-22 mm at the end of the drought period (Autumn 2000).

Comparing the vertical displacement of the PSs with rainfall deficit shows a relationship between the curves (Fig. 9). This could be related to shrinkage of the soil durin the drought period. In order to quantify the subsidence related to shrinkage of these clay soils, a map of ground displacement during the same period (May 1998 – November 2000) was constructed by interpolating the vertical settlement from individual PSs (Figure 7).

A large number of municipal water wells are also present within the zone showing the maximum subsidence. Comparing abstraction with PS displacement (Figure 10) shows quite a good correspondence between the increase in water pumping after 1998 and the settlement in the same period. The lowering of the water table associated with pumping well could therefore contribute to ground settlement.

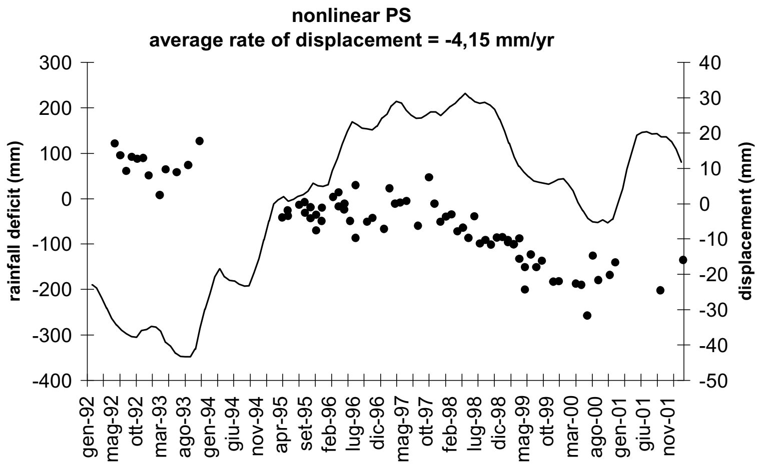

Figure 9. Rainfall deficit vs. PS displacement series (sub-unit "silty clay with layer of sand").

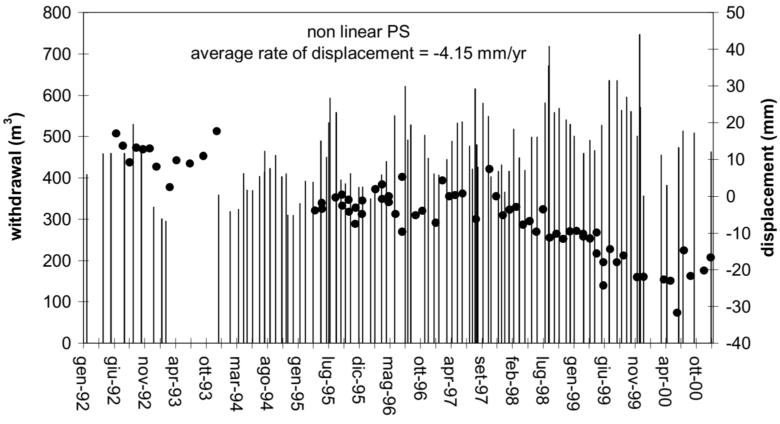

Figure 10. Daily withdrawal vs. PS displacement series (sub-unit "silty clay with layer of sand").

CONCLUSIONS

A methodology has been proposed for engineering geological mapping in support of urban planning and development in the Oltrepo Pavese area. The method is based on engineering geological units defined for a maximum thickness of 15 m (zones that may be regarded as homogeneous from a geomorphological and engineering geological point of view). Eight engineering geological units were identified in the plain area of the Oltrepo Pavese. The zoning provides a basis for planning appropriate geotechnical testing in order to define local situations which require more detailed studies. Pertinent knowledge of the subsoil conditions have a fundamental effect on selecting appropriate foundations and facilitates the planning of site investigation, the recognition of potential soil and foundation problems.

Corresponding author: Dr Claudia Meisina, Department of Earth Sciences, University of Pavia, Via Ferrata n°1, Pavia, 27100, Italy. Tel: +39 0382 985831. Email: cmeisina@manhattan.unipv.it.

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