Geotechnical modelling of the subsoil of Rome (Italy) by means of multivariate geostatistics

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ABSTRACT: A research project was carried out by the C.N.R. to develop an integrated geological-geotechnical model of the subsoil of Rome. Data of more than 6000 boreholes were archived in a GIS and used to develop the geological model; the results presented in this work mainly focused on the upper Pleistocene-Holocene alluvial deposits. Information of more than 2000 boreholes penetrating the alluvial deposits was encoded and elaborated using geostatistics to model the sedimentary bodies. Spatial variability of the physical and mechanical properties was also investigated to develop the geotechnical model. Multiple linear regression, kriging, and cokriging were applied to estimate the drained friction angle φ'; cross-validation demonstrates the cokriging with the PCA factors as auxiliary variables being the most suitable method. In progress work on cokriging of φ' using granulometries as auxiliary variables demonstrates this approach to be viable for future applications.

KEYWORDS: alluvial deposits, geotechnical properties, multivariate geostatistics, PCA, Rome.

1. Introduction

Public administrations and agencies of Civil Protection are continuously involved in the managing of environmental hazards and planning of future development in urban areas, which both require in-depth knowledge of the underground. The National Research Council (C.N.R.) has coordinated during the last two years a multidisciplinary research group to develop an integrated geological-geotechnical model of the subsoil of Rome (Italy). Geological information was collected from public administrations and private companies during the first stage of the project. Data of more than 6000 geotechnical boreholes were homogenized and archived in an ArcGIS geodatabase. During the second stage of the research, more than 3000 boreholes were selected from the database, interpreted and correlated to implement a geological model (Cavarretta and others, 2005), whose target is the modelling of the geotechnical properties. Attention was mainly focused on the upper Pleistocene-Holocene alluvial deposits, which occupy a sizable and densely populated part of the city. The modelling of the main lithofacies of the alluvial deposits is currently carried out with geostatistics: sedimentary bodies are reconstructed estimating lithological/textural associations, and their internal organization will be simulated applying suitable sedimentological constrains. In this paper, an attempt to also apply multivariate geostatistics to the geotechnical modelling of the alluvial deposits is described, and the first results for the spatial modelling of the drained friction angle from direct shear test (φ') are shown. The possibility of using physical parameters as auxiliary variables to improve the estimation of the mechanical parameters is also discussed.

2. Geological and stratigraphic setting

The City of Rome is located on the Tyrrhenian margin of the Italian peninsula, at the convergence between the central and the northern Apennines. The substrate of the city originates from the continuous superimposition of marine and continental sedimentary deposits (Funiciello, 1995), which are interfingered with products of the surrounding volcanic districts (Fig. 1). In historic times, damming of the water courses, land reclamation, and quarry activities have modified the original morphology of the Roman countryside, at present hidden by a thick blanket recording the continuous anthropic activity of the last 3000 years.
The recent alluvial deposits have developed during the last glacial-interglacial cycle of post-Tyrrhenian age (post-125 ka BP). Information of more than 2000 boreholes crossing the alluvial deposits was encoded and processed to define the stratigraphic organization and the lithofacies distribution. Three main lithofacies were recognized: 1) the basal *pebbles and sandy pebbles*, with a lower boundary ranging from north to south from -35 m to -60 m below the present sea-level, and a thickness ranging between 5-10 m and 20-25 m in the same direction; 2) the intermediate *organic rich clays with frequent lens of sands and subordinate lens of pebbles*, with a thickness between 20 m and 40 m from north to south; 3) the upper *silty clays with subordinate lens of sands*, with a nearly constant thickness of 20-25 m along the investigated alluvial plain.

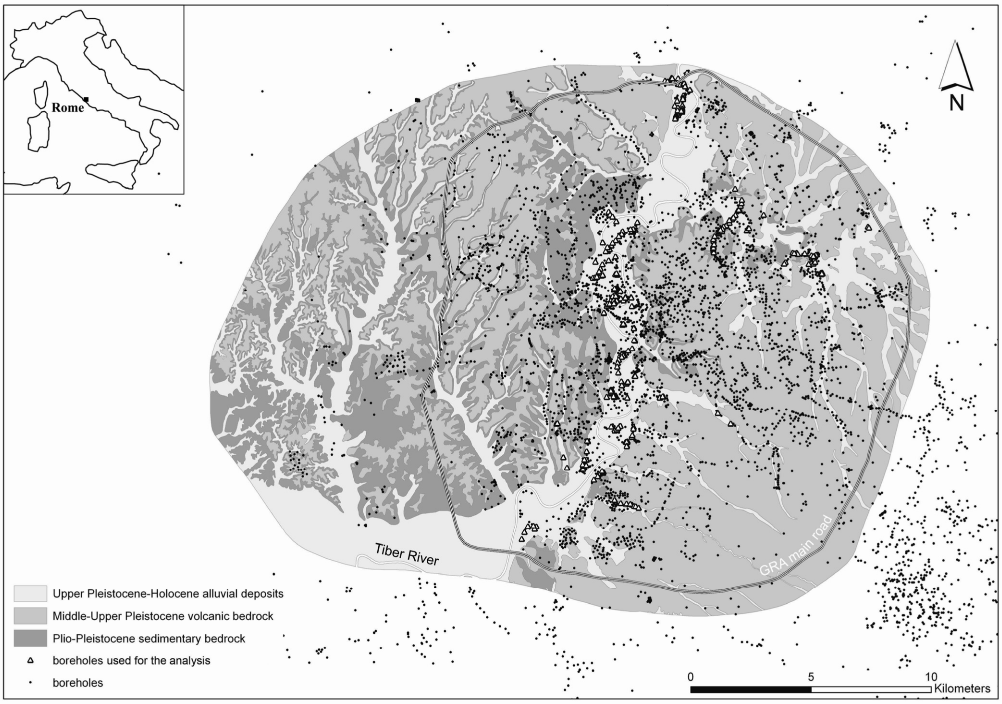
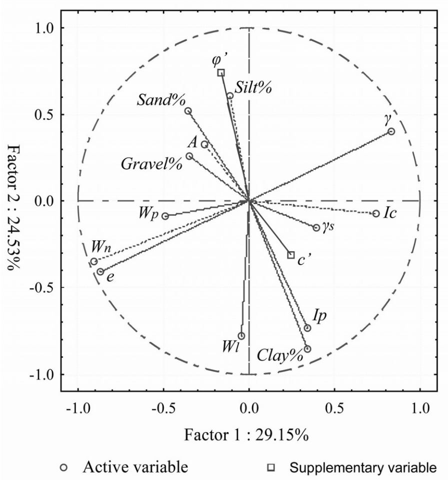


Fig. 1. Schematic geologic map of the study area with the location of the boreholes.

3. Principal Component Analysis of the geotechnical parameters

The geotechnical information concerning 950 samples refers to more than 700 boreholes penetrating the alluvial deposits. 55 samples out of 950 have a complete set of the geotechnical information and were analyzed to characterize the most relevant 13 physical properties – total unit weight (γ), unit weight of soil particles (γ_s), natural water content (w_n), liquid limit (w_l), plastic limit (w_p), plasticity index (*Ip*), consistency index (*Ic*), clay activity (*A*), void ratio (*e*), gravel percentage (*Gravel%*), sand percentage (*Sand%*), silt percentage (*Silt%*), clay percentage (*Clay%*) – and 2 mechanical parameters – drained friction angle from direct shear test (φ'), and drained cohesion from direct shear test (c').

Principal Component Analysis, PCA, was applied to investigate the relationships among the 15 parameters, using the mechanical ones as supplementary variables. Because of the redundancy of information, the first five principal factors of the PCA explain more than the 85 % of the total variability; specifically, the first two factors explain more than the 50 % of the total variability. Factor 1 explains the 29.15 % of the total variability and is probably related to the porosity of the sample (Fig. 2). Factor 2, strongly correlated with φ', explains the 24.55 % of the total variability and is likely controlled by the amount and the mineralogical composition of the clay component (Fig. 2). Instead, the drained cohesion c' is weakly correlated with the Factors 1 and 2 and has a moderate correlation with the Factor 4 (Fig. 2), which explain about the 9.90 % of the total variability.



	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5
γ	0.8337	0.4020	0.1285	0.0028	-0.1077
γ_s	0.3904	-0.1549	-0.4364	0.4246	0.0697
w_n	-0.9098	-0.3516	0.0313	-0.0346	0.0644
w_l	-0.0418	-0.7822	0.5393	0.1761	-0.1146
w_p	-0.4872	-0.0909	0.3795	0.7460	-0.0538
I_p	0.3386	-0.7368	0.2619	-0.4033	-0.0753
I_c	0.7434	-0.0758	0.4041	0.4206	-0.1087
A	-0.2627	0.3252	0.6070	-0.3992	-0.1968
e	-0.8723	-0.4053	-0.1063	0.0393	0.1510
Gravel%	-0.3506	0.2591	0.1423	0.0354	-0.7424
Sand%	-0.3595	0.5229	-0.4495	0.0997	-0.3071
Silt%	-0.1087	0.6124	0.5597	0.0249	0.4703
Clay%	0.3385	-0.8520	-0.2191	-0.0727	-0.1274
φ'	-0.1605	0.7413	-0.1444	0.0150	-0.2178
c'	0.2482	-0.3147	-0.1864	0.5211	-0.0576

Fig. 2. Score plot of the geotechnical parameters used for the PCA (left) and factors/properties table (right).

4. Estimation of the drained friction angle

The application of PCA demonstrates the possibility of using physical parameters as auxiliary variables to improve the estimation of the mechanical parameters, particularly of the drained friction angle φ'. On this subject, a cross-validation analysis of the φ' values estimated with multiple linear regression, kriging, and cokriging with the PCA factors as auxiliary variables was performed; results demonstrate the estimation improves by introducing the physical parameters (Fig. 3a).

By the way, not all the samples have all the physical parameters; on the contrary, granulometries are recorded for 902 samples out of 950. An attempt to estimate φ' using granulometries as auxiliary variables was made using the 902 samples with the textural information. A cross-validation analysis of the φ' values estimated with multiple linear regression, kriging, and cokriging with granulometries as auxiliary variables was again performed. This application demonstrates the cokriging using *Clay%* and *Sand%+Gravel%* as auxiliary variables being a good estimator of φ' (Fig. 3b); *Silt%* is weakly correlated with φ' (-0.38) and using this parameter the estimation worsen. This behaviour is probably due to the different contribution of the silty component to the shear strength, when silt is associated with finer (i.e. clay) or coarser (i.e. sand and gravel) material. In a future steps of the research the percentage of silt will be integrated in the estimation of *φ'* trying to use non-linear estimators.

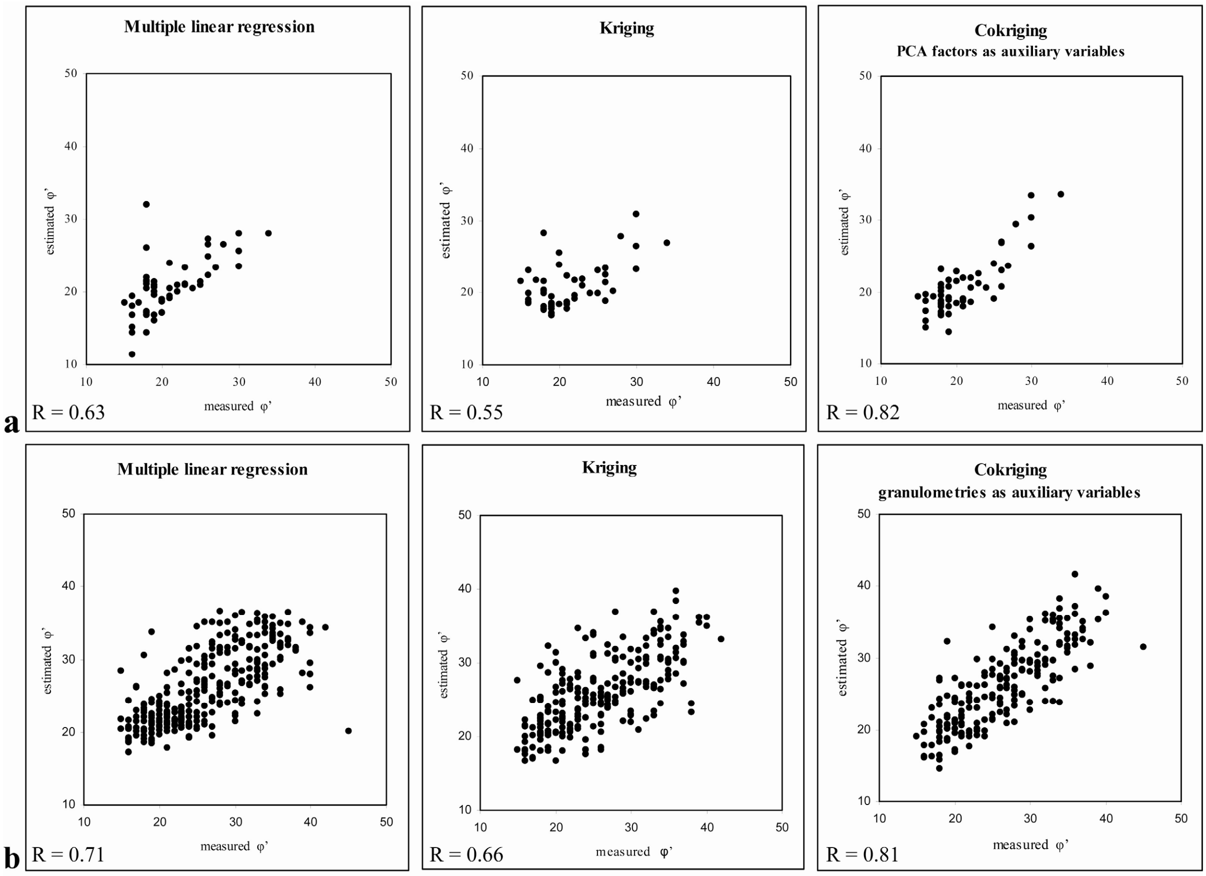


Fig. 3. Scatterplots of measured/estimated *φ'*. 3a) cross-validation performed on 53 samples; 3b) cross-validation performed on 295 samples using *Clay%*, *Silt%*, and *Sand%+Gravel%* for multiple linear regression, and *Clay%* and *Sand%+Gravel%* as auxiliary variables for cokriging.

5. Conclusions

A research project was carried out by the C.N.R. to develop an integrated geological-geotechnical model of the subsoil of Rome. The results presented in this work mainly focused on the upper Pleistocene-Holocene alluvial deposits. Principal Component Analysis, PCA, was used to investigate the relationships among the geotechnical parameters of 55 selected samples. Cokriging estimation of the drained friction angle *φ'*, using the PCA factors as auxiliary variables, is demonstrated being the most suitable estimation method. In progress work also demonstrates the cokriging of *φ'* to be viable using just granulometries as auxiliary variables. Nevertheless, application of multivariate geostatistics demonstrates its validity for the geological-geotechnical modelling of the underground of Rome. The future challenge is the proper integration of the geological and geotechnical information from the sample scale to the lithofacies scale, i.e. moving from granulometry to lithology.

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