Geotechnical map of Holocene alluvial soil deposits in the metropolitan area of Granada (Spain): a GIS approach

I. Valverde-Palacios · I. Valverde-Espinosa · C. Irigaray · J. Chacón

Abstract The results of a geotechnical research on Holocene alluvial deposits in 14 municipalities of the Granada basin are presented, and a procedure to draw a geotechnical map of foundation conditions, using ArcGIS 9.3 (ESRI 2009) is described. Three different alluvial soil units were distinguished: (1) cohesive soils; (2) cohesive and fine granular soil; (3) coarse granular soil, based on their properties concerning grain size, bulk density, cohesion, internal friction angle, and N_{SPT} value. The actual building structures have predominantly shallow foundations. The definition of the minimum depth to actual foundation level was based on the analysis of thickness of disturbed soils, man-made fillings, depth to the water table and bearing capacity. The depth to actual foundation levels varies from 0.5 to 4 m in the study area. Concerning the ground, the geotechnical data compiled on foundation conditions show a high heterogeneity expressed by the spatial distribution of the basic properties in the three distinguished units of cohesive, cohesive and fine-granular, and coarse granular soils, respectively. The fine-grained alluvial soil units (cohesive) have a low bearing capacity varying between 40 and 100 kPa and are associated with a shallow water table appearing near the surface. In contrast, across the wide extension of the coarse-grained alluvial soil unit, a bearing capacity ranging from 60 to 300 kPa is determined; this unit is associated with a deep water table appearing at more than 40 m below the surface. The usefulness of the obtained geotechnical map of foundation conditions extends to the analysis of further alternatives of urban expansion and for the delimitation of future trends for of land-use-development processes in the metropolitan area of Granada, mainly at local and regional scales.

Keywords Alluvial soils · GIS · Spatial distribution · Geotechnical parameters · Metropolitan area of Granada · Spain

Résumé Les résultats d'une étude géotechnique sur des alluvions holocènes dans 14 communes du bassin de Grenade sont présentés, et une procédure de dessiner une carte géotechnique des conditions de fondation, en utilisant ArcGIS 9.3 (ESRI 2009) est décrite. Trois unités de sols alluviaux différents ont été distingués: (1) des sols cohésifs, (2) le sol granulaire cohésif et fine, (3) sol granulaire grossier, en fonction de leurs propriétés relatives à la taille des grains, la densité, la cohésion, angle de frottement interne et la valeur NSPT. Les structures de bâtiments réels ont des fondations en majorité peu profondes. La définition de la profondeur minimale au niveau de la fondation réelle est basée sur l'analyse de l'épaisseur des sols perturbés, les plombages d'origine humaine, la profondeur de la nappe phréatique et la capacité portante. La profondeur au niveau des fondations réelles varie de 0,5 à 4 m dans la zone d'étude. En ce qui concerne le sol, les données géotechniques recueillies sur les conditions de fondation montrent une grande hétérogénéité exprimée par la distribution spatiale des propriétés fondamentales dans les trois unités distinguées de sols cohésif, cohésive et granulaire cohésif, et grossier,

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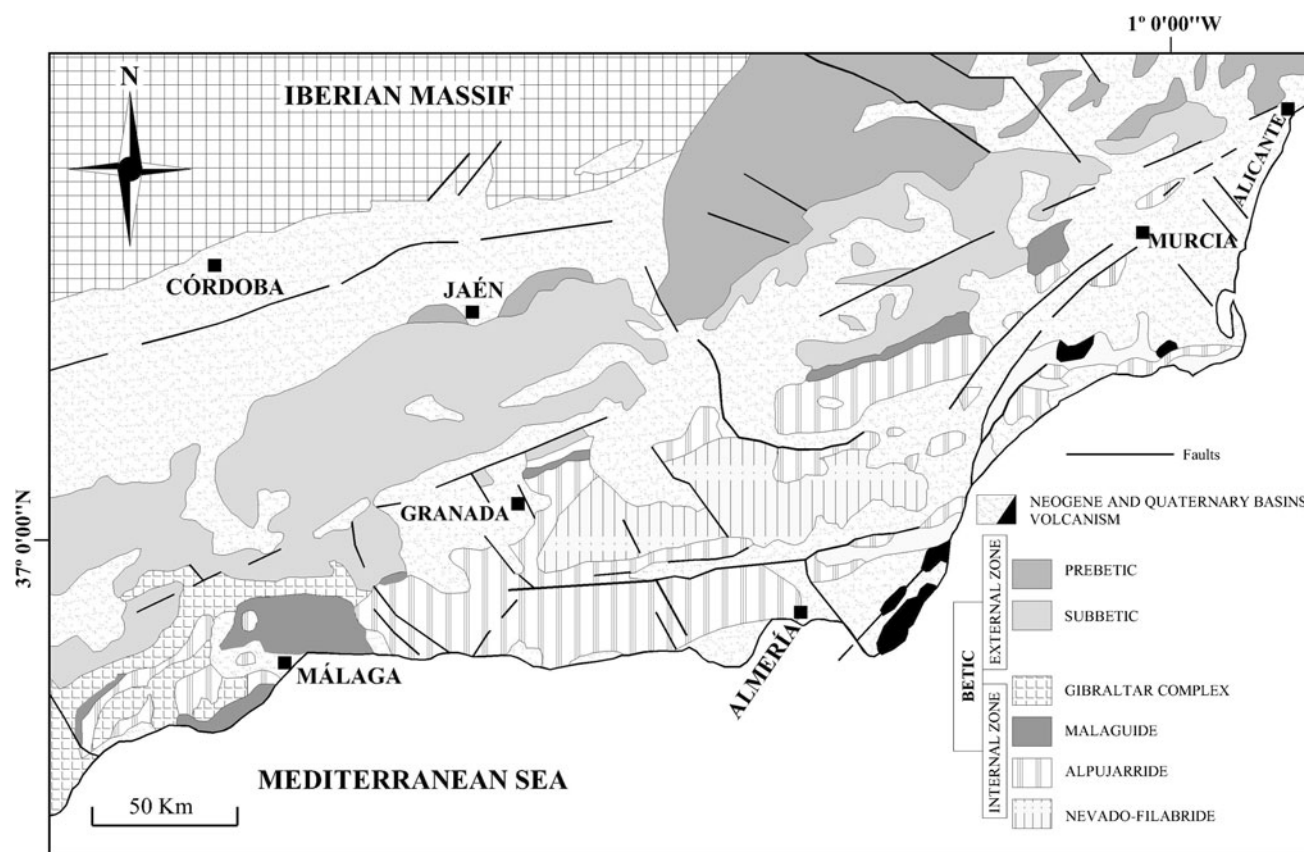
Fig. 1 Geological sketch of the central and eastern part of the Betic Cordillera (modified from Sanz de Galdeano et al. 2010)

respectivement. Les unités de sols alluviaux à grains fins (cohésif) ont une faible capacité portante variant entre 40 et 100 kPa et sont associées à une nappe phréatique peu profonde apparaissant près de la surface. En revanche, à travers la large extension de l'unité de sol alluvial à gros grains, une capacité de charge allant de 60 à 300 kPa est déterminée, jusqu'à ce que cette unité soit associée à une nappe d'eau profonde figurant à plus de 40 m sous la surface. En revanche, de l'autre côté de la grande extension de l'unité d'alluvions à gros grains, une capacité de charge comprise entre 60 et 300 kPa est déterminée; cette unité est associée à une nappe d'eau profonde apparaissant à plus de 40 m au-dessous de la surface. L'utilité de la carte géotechnique obtenue montrant les conditions de fondation s'étend à l'analyse d'autres alternatives de l'expansion urbaine et de la délimitation des tendances futures pour des procédés d'affectation et la planification du territoire dans la région métropolitaine de Grenade, principalement à l'échelle locale et régionale

Mots clés sols alluviaux · SIG · Distribution spatiale · paramètres géotechniques · région métropolitaine de Grenade · Espagne

Introduction

The main objective of this research was to gain fuller knowledge of the geotechnical parameters of the soil as support for a geotechnical map for building foundations (Valverde-Palacios et al. 2012) as a tool for new building projects and also for the inspection of existing structures[1]. Also, the aim is to devise methods for preventing and reducing structural damage resulting from foundation failures that result from incompatibility with the geotechnical parameters and properties of the subsoil in each sector. The geological, tectonic, and seismic characteristics of the Granada basin have been extensively studied (Dabrio et al. 1978; García Dueñas 1969; Castillo Martín 1986; Vidal 1986; Morales et al. 1990; Sanz de Galdeano et al. 2001; Galindo-Zaldívar et al. 2003; Rodríguez-Fernández and Sanz de Galdeano 2006). Also, some papers on the geotechnical seismic

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[1] The "Vega" of Granada is an area of traditional fertile farming land surrounding the city of Granada. The geotechnical properties and foundation conditions of the Holocene alluvial soils of the "*Vega*"of Granada (Spain) are very heterogeneous, not only because of the variability of the lithological and granulometrical distribution, but also because of the changeable setting of the water table in the area.

features of the basin have been published (Chacón et al. 1988, 2012; Valverde-Palacios et al. 2012) as well as detailed geotechnical and seismic profiles for the subsoil of the city of Granada (Hernández Del Pozo 1998 and Cheddadi 2001).

Many existing structures were built before the regulation of the current "Building Technical Code (CTE; BOE 2006)". Typically, before 1950 it was common to support foundations on stripped trenches filled with cobblestone, loose gravel, pebbles, or boulders or with simple foundation structures, such as loading walls made on adobe, "tapial" (old traditional compressed earth wall), dry masonry, brick, or ashlars, in this case essentially under old monumental buildings. Since 1995, under the guidance of the new "Spanish Earthquake-Resistant Construction Codes" and its later reviews (up to the current "NCSR-02"; BOE 2002), there was a considerable reduction of foundations with isolated footings and a parallel increase of stripped footings with bracing and reinforced plates as shallow foundation typologies; even pilings were used—particularly for underground works (Chacón et al. 2012; Valverde-Palacios et al. 2012).

In the main villages of the metropolitan area of Granada, about 62 % of buildings are two-floor family homes, and some 32 % are one-floor service buildings, from which only 6 % have a basement floor.

The use of GIS in the preparation of geotechnical, hazard, and risk maps is now widespread, and many papers also including some on areas surrounding the Granada basin (Chacón et al. 1992, 2006; Irigaray et al. 2007; Jiménez-Perálvarez et al. 2011; Irigaray et al. 2012) treat these topics. There are also papers on the treatment and analysis of the spatial distribution of geotechnical parameters (Luzi et al. 2000; Deffontaines et al. 2001; Zhu and Liu 2005; Robinson and Metternicht 2006; Yilmaz 2008; Mohammed et al. 2010; El May et al. 2010).

The research was performed in four stages: (1) data collection and compiling of a geotechnical database (soil profiles from drill holes, SPTs, undisturbed samples, and laboratory tests); (2) geo-referencing of each geotechnical report and the elaboration of building-attribute tables; (3) application of different interpolation methods for better results and higher graphical information levels; and (4) preparation of maps showing the spatial distribution of the
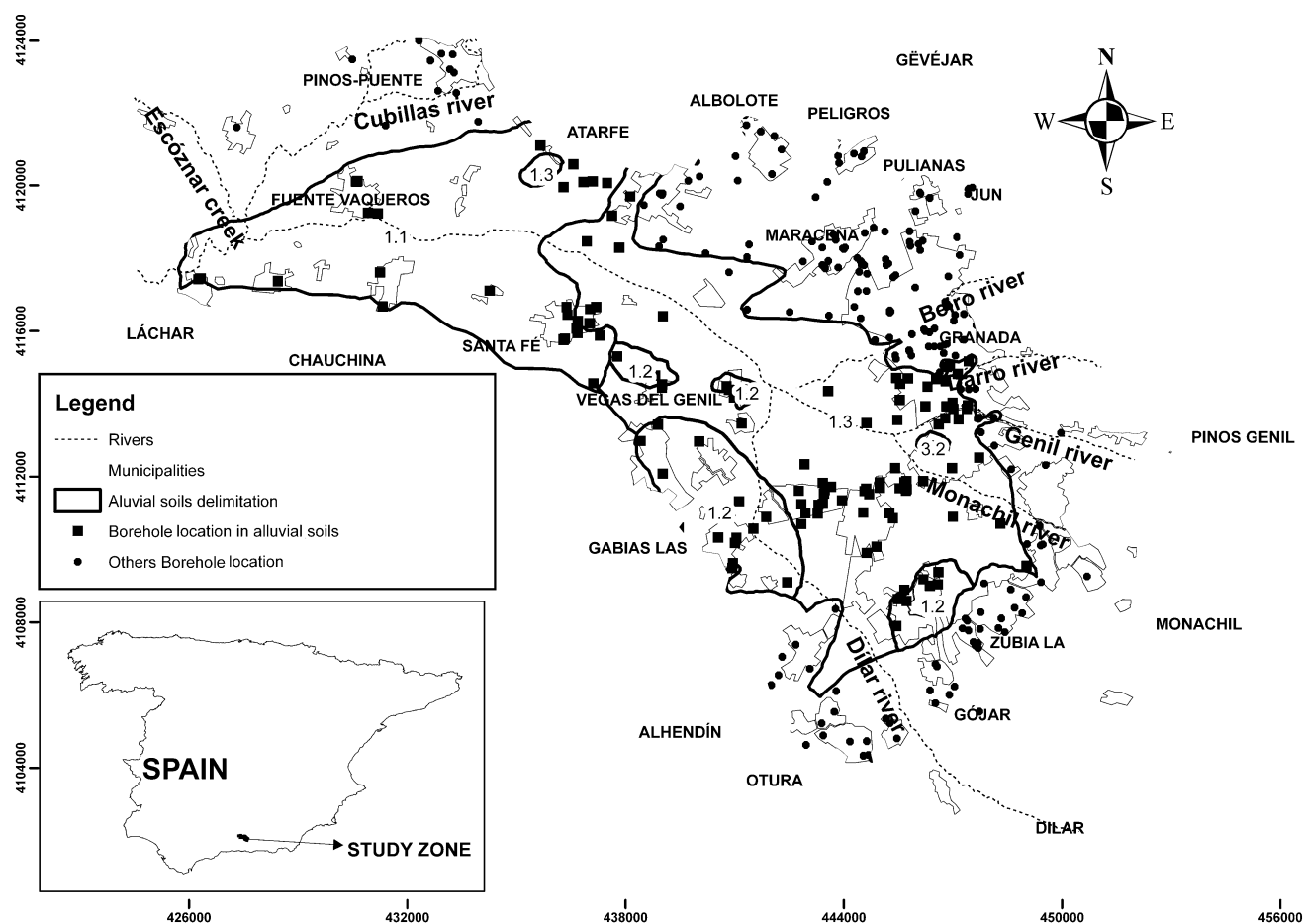

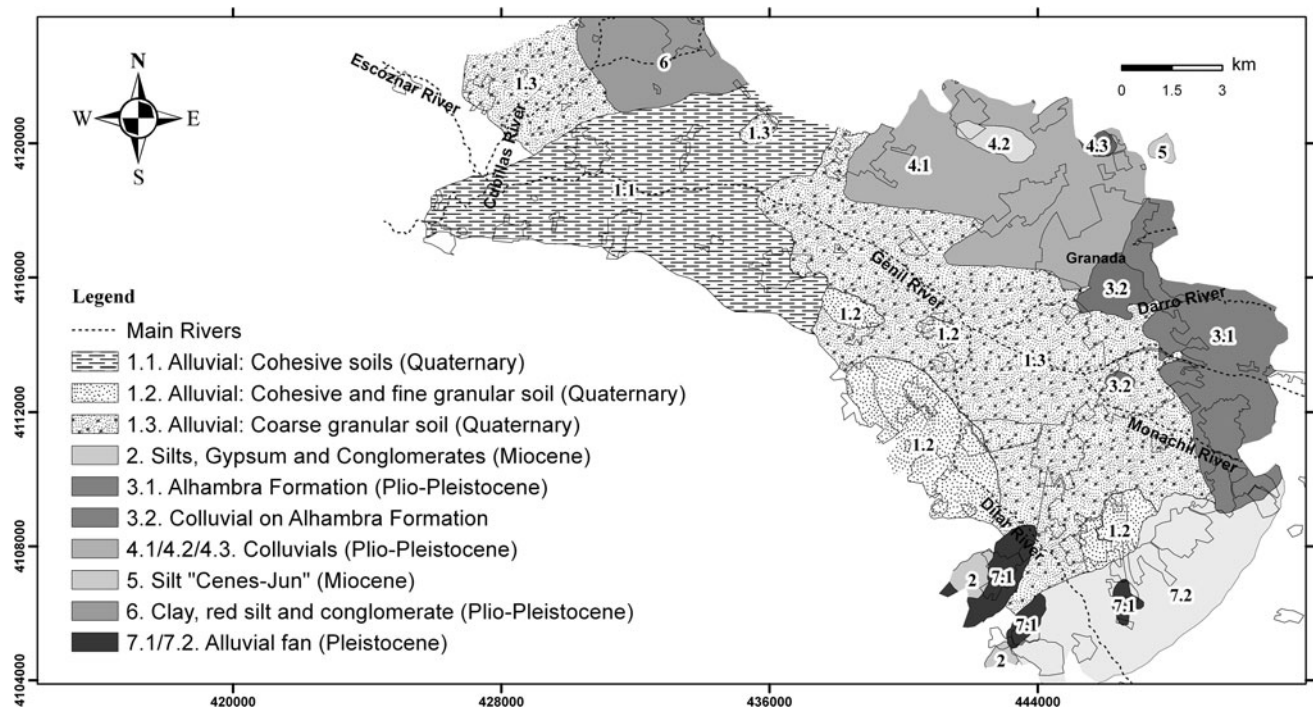**Fig. 2** Geographical setting of the study area. Drill holes are shown

Fig. 3 Spatial location of soil units, zones and subzones

geotechnical parameters by means of GIS software ArcGis 9.3 (ESRI 2009).

Geological setting and geotechnical properties of alluvial soils

The Granada basin lies in the central part of the Betic Cordillera along a NE-SE belt separating the Sub-Betic domain or external zones from the Betic domain or internal zones. It is one of a set of intra-mountain basins that developed in the Neogene period during post-orogenic events of tectono-sedimentary deposits. The basin is composed of Miocene to Holocene deposits attaining a thickness of over 2 km in certain areas (Morales et al. 1990; Sanz de Galdeano et al. 2010). The *Vega* (agricultural land) of Granada is a highly irrigated alluvial plain, deposited in Late Pleistocene and Holocene times on the banks of the Genil River and its tributaries in the NW part of the Granada basin. These alluvial deposits reach some 400 m in thickness according to recent deep geophysical surveying (Rodríguez-Fernández and Sanz de Galdeano 2006). All of these watercourses descend from the surrounding hills and deposit sediment in the predominantly Holocene Vega, between the towns of Cenes de la Vega and Láchar (Fig. 1).

A large area was analysed, covering 298 km² in Holocene alluvials on both banks of the Genil River (Fig. 2)

located in the municipalities of Armilla, Atarfe, Chauchina, Cijuela, Cúllar Vega, Churriana de la Vega, Fuente Vaqueros, Granada, Lachar, Las Gabias, Ogíjares, Pinos Puente, Santa Fe, and Vegas del Genil. These are 14 out of a total of 32 municipalities that make up the metropolitan area of Granada (Spain).

The zones and subzones (Fig. 3) were delimited based on their lithology, laboratory tests and SPT test (Particle Size Analysis Test ASTM D422—63, 2002; Atterberg Limit Tests, ASTM D4318-10; Standard Penetration Test (SPT) ASTM D11951586—08a; Consolidation Test, ASTM D2435/D2435 M—11, Sulphate Content tests, ASTM C1580—09e1 tests, only to specify each type cement for foundation; Unconfined Compressive Strength Test, ASTM D2166-00 and Direct Shear Test, ASTM D3080).

The soil units have some common features useful for the overall definition of each zone. In this context, subzones are subdivisions in groups of soil units taking into account only some particular physical and mechanical properties featuring some particular soil units but not all the soil units composing a zone. In general, the main distinction is based on grain size (cohesive, coarse or mixture cohesive/fine-granular). For example, the alluvial soils (soil unit, zone 1) were divided into two main subzones: 1.1 Cohesive soil and 1.3 Coarse granular soil. Additionally, a third subzone was used, 1.2 cohesive and fine-granular soil, to describe an alluvial with many changes in its grain size and other
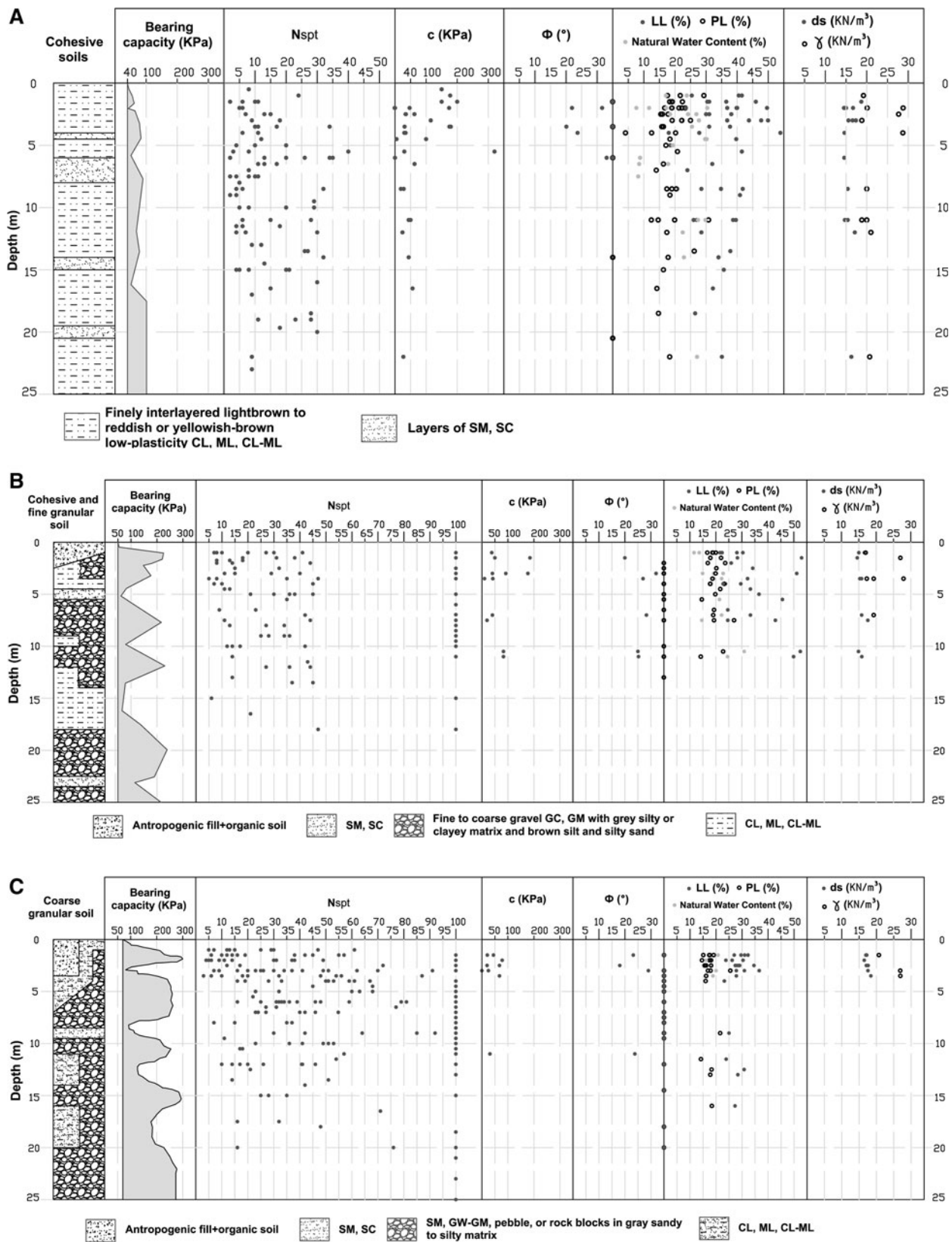
Fig. 4 Geotechnical profiles showing vertical distribution of soil and results of in situ (N_{SPT}, bearing capacity) and laboratory tests (cohesion, friction angle, specific weights) **a** 1.1. Cohesive soils; **b** 1.2. Cohesive and fine-granular soil; **c** 1.3. Coarse granular soil
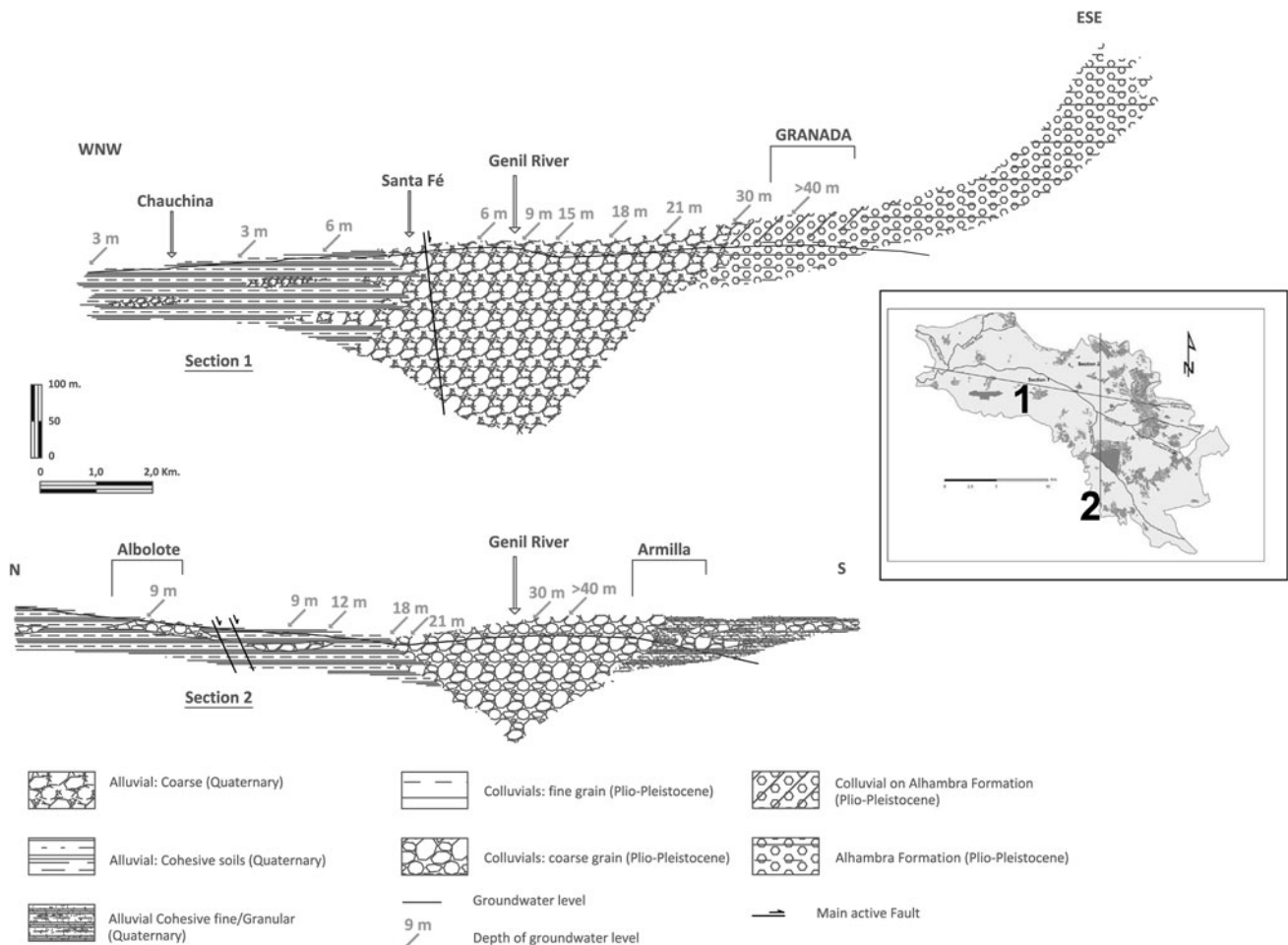
Fig. 5 Cross sections across the metropolitan area in the Granada Basin

mechanical and physical properties. Also, the geographic location is taken into account.

If the lithological column of the borehole shows predominance of fine alluvial soils, then it can be classified as Subzone 1.1. "Cohesive Soil" (Fig. 4a), but if coarse granular soils represent the greater percentage, this location is classified as Subzone 1.3 (Fig. 4c). On the other hand, if the lithological column shows alternate layers of cohesive and granular soils, it is assigned to Subzone 1.2.

Figures 4a–c, and 5 clearly reflect the heterogeneity of the geotechnical profiles. These three sub-zones were found to have the following types of alluvial soil and predominant foundation solutions:

1.1 *Cohesive soils* (Fig. 4a), composed of light-brown to reddish or yellowish-brown low-plasticity clay (CL), silt (ML), silty clay and clayey silt (CL–ML) with minor amounts of thin layers of granular soil (SM, SC). The depth to the water table is 1–10 m. Shallow rigid foundation with high capacity of loading distribution and type of structural concrete plate with thickness around 0.60 m.

1.2 *Cohesive and fine granular soil* (Fig. 4b), composed of thin, irregularly alternating layers of cohesive (brown to reddish-brown clayey silt and silty clay CL–ML), and granular soils (fine to coarse gravel CG, CM with grey silty or clayey matrix and brown silt and silty sand) of predominantly low plasticity. The water table in this unit varies in depth from 10 to 150 m, a situation that permits foundations without any special drainage treatment except in building projects with several basement floors. Shallow strip footing or structural concrete plate with thickness above 60 cm.

1.3 *Coarse granular soil* (Fig. 4c), composed of silty sand (SM), silty to well-graded gravel (GW-GM), pebbles and some rock blocks in grey sandy to silty matrix with decimeter-thick layers of sandy silt (ML with sand) and fine to middle silty sand (SM) as lenses in the first three meters of the profile. The water table is at depth of 4–50 m, a variation that may be taken into account in order to include drainage solutions in basement floors and foundations as well as underground works. Usually, shallow strip
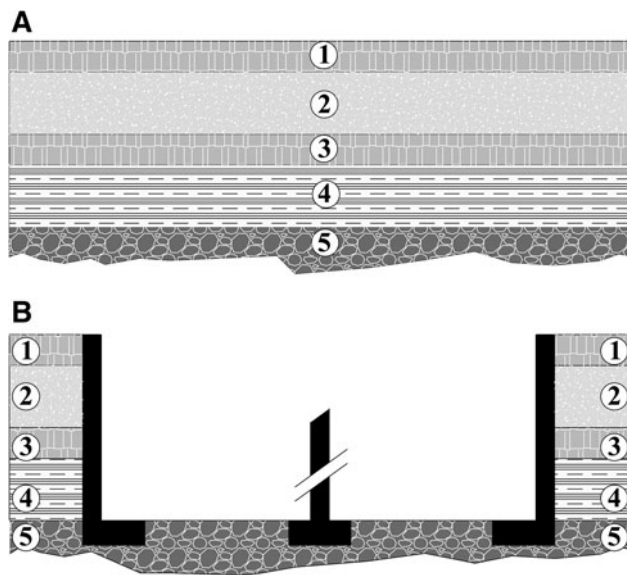
Fig. 6 a Schematic arrangement of layers b Minimum depth of foundation. *1* top vegetable soil, *2* anthropogenic fill, *3* buried vegetable soil, *4* soft soil with very low bearing capacity, *5* alluvial: coarse granular soil

footings or plates of structured concrete deep foundations by pilling are frequent on deep cohesive soils and infills in Atarfe and parts of central Granada Town.

Geotechnical parameters

The geotechnical profiles in Fig. 4 and cross sections in Fig. 5 were based on information from 141 drill holes, in which 507 SPTs were made, and 410 disturbed and undisturbed samples obtained from laboratory testing, following the previously mentioned ASTM technical norms.

In addition, more in situ data were collected from 213 dynamic penetration tests and 107 trenches. Furthermore, median values ("mode" in the case of USCS classification) were used to evaluate 365 grain-size distribution tests, 339 Atterberg consistence tests, 66 compressive unconfined strength tests, 50 undrained direct shear tests, 20 oedometer or consolidation tests under vertical loads ranging between 10 and 400 kPa, and 186 sulphate-content tests to establish the "exposure class" according to "Spanish Technical Code for structural concrete, EHE-08″ (BOE 2008b, c).

Finally, for the regionalization of properties to draw the geotechnical maps and its further analysis, for each drill hole (Fig. 2), at the foundation depth, the following parameters, represented by its median, were entered into ArcGIS (ESRI 2009) as attribute tables: bulk density, cohesion, internal friction angle, modulus of subgrade reaction from 1 ft^2 plate load test of (Eurocode 7, 2000), depth to water table, N_{SPT} values and minimum depth

(Fig. 6) of foundation. This depth is obtained by adding the thickness of different soil layers: anthropogenic fill, top vegetable soil, buried vegetable soil below the anthropogenic soil infilling and soft soil with very low bearing capacity. The final purpose is generating a characteristic geotechnical map showing ranges of variability of each parameter in a continuous surface at the minimum depth of foundation, characterized by the median values of each parameter at this depth.

Discussion of the results

Geotechnical and water table data

In Table 1, the geotechnical heterogeneity of the Holocene alluvial deposits of the Vega of Granada is shown with details, by statistical parameters, about the cohesive soils (Zone 1.1) and cohesive and fine-granular soil (Zone 1.2), with minor amounts of fine sandy layers, appearing in the NW sector, and the coarse granular soils (Zone 1.3) predominant in the central and SE sector of the study zone. This textural variability is clearly expressed by its mechanical properties and geotechnical behaviour.

In general, the observed data show an asymmetric distribution (skewness different from zero). In order to indicate the central tendency, it is customary to calculate the mean, but in an asymmetric distribution, the mean is a mistaken parameter. In these cases, the median is more suitable. The median is the numerical value separating the higher half of a data sample from the lower half.

In all cases, the most appropriate parameter to characterize the data is the median because the sample distribution is not normal, even though, in some cases, mean and median are close (e.g., internal friction angle and modulus of subgrade reaction for cohesive and coarse soils). For the soil classification (USCS) the mode was used.

Thereby, the N_{SPT} ranged between 5 and 20 (median 10), corresponding to a loose to medium-density index (Terzaghi and Peck 1948) in the Zone 1.1 and between 15 and 50 blows (median 30), corresponding to medium dense to very dense density index values (Terzaghi and Peck 1948) for the Zone 1.3. About cohesion parameter its median value is 100 kPa (range from 100 to 300 kPa) for cohesive soils and null for non-cohesive for the case of zone 1.3. The internal friction angle in this alluvial soil is between 20 and 36°. Furthermore, the median value is 22 for zone 1.1 and 35 for zone 1.3.

Finally, the ultimate bearing capacity limited by the shear failure of soil below and adjacent to the foundation (Terzaghi 1943; Meyerhof 1963; Hansen 1970) or by foundation settlement (Schmertmann 1975) varied between 40 and 100 kPa (median 60 kPa) in Zone 1.1, 50 and 250

Table 1 Summary of geotechnical parameters (Valverde-Palacios 2010) and statistical evaluation: σ_{adm} (kPa), ultimate bearing capacity; c (kPa), cohesion; Φ^o, internal friction angle; Ks_1 (kN/m^3), modulus of subgrade reaction (Ks_1) from 1 ft^2 plate load test of (Eurocode 7, 2000); φ (kN/m^3), bulk density; N_{SPT}, number N Standard Penetration Test; LL (%), liquid limit; PL (%) plastic limit; PI (%) plasticity index; #200 (%), percentage of fine fraction passing sieve n°200 ASTM; D50, soil grain size at 50 %; USCS, soil symbol Unified System of Soil Classification, Wagner (1957)

Properties	Statistics values	Zone 1.1. Holocene: cohesive soils	Zone 1.2. Holocene: cohesive fine/granular soil	Zone 1.3. Holocene: coarse granular soil
σ_{adm} (kPa)	Minimum	40	50	60
	Maximum	100	250	300
	Standard deviation	22	61	4.7
	Mean	64	118	220
	Median	60	120	250
	Skewness	0.56	0.78	−1.69
c (kPa)	Minimum	100	0	0
	Maximum	300	700	0
	Standard deviation	80	23.39	0
	Mean	160	121	0
	Median	100	0	0
	Skewness	0.83	1.82	
Φ (°)	Minimum	20	20	30
	Maximum	24	36	36
	Standard deviation	0.98	5.55	1.73
	Mean	21.68	27.57	34.25
	Median	22	30	35
	Skewness	−0.51	−0.35	−1.14
Ks_1 (kN/m^3)	Minimum	19,600	29,400	39,200
	Maximum	58,800	117,600	117,600
	Standard deviation	14,847	22,206.8	16,140.6
	Mean	39,200	50,048.6	78,390.2
	Median	39,200	39,200	78,400
	Skewness	−0.06	1.38	−0.14
φ (kN/m^3)	Minimum	18	18	18
	Maximum	20	20	20
	Standard deviation	0.9	0.9	0.52
	Mean	18.9	18.5	18.3
	Median	19	18	18
	Skewness	0.14	1.04	1.38
N_{spt}	Minimum	5	8	15
	Maximum	20	30	50
	Standard deviation	5.28	8.27	4.22
	Mean	10.46	17.64	27.78
	Median	10	15	30
	Skewness	0.62	0.42	−1.77
LL (%)	Minimum	0	0	0
	Maximum	54.4	56.9	25
	Standard deviation	11.5	17.96	3.69
	Mean	32.9	17.35	0.63
	Median	35	21.65	0
	Skewness	−1.37	0.45	5.93
PL (%)	Minimum	0	0	0
	Maximum	34.3	27	21.6
	Standard deviation	6.3	9.95	2.60
	Mean	17.5	10.39	0.4
	Median	18.3	15.39	0
	Skewness	−1.02	−0.02	6.46

Table 1 continued

Properties	Statistics values	Zone 1.1. Holocene: cohesive soils	Zone 1.2. Holocene: cohesive fine/granular soil	Zone 1.3. Holocene: coarse granular soil
PI (%)	Minimum	0	0	0
	Maximum	33.7	35.7	11.9
	Standard deviation	7.2	9.35	1.26
	Mean	15.4	5.81	0.19
	Median	15.7	2.85	0
	Skewness	−0.25	1.93	7.49
#200 (%)	Minimum	51	3.6	1.4
	Maximum	99.5	98.2	47.52
	Standard deviation	12.7	31.06	10.17
	Mean	82.6	50.09	13.14
	Median	86.3	47.09	9.9
	Skewness	−0.66	−0.03	2.03
USCS	All distinguished types	CL, ML, CL–ML, CH, with thin layers of SM, SC	CH, CL, CL–ML ML, GC–GM, GP, GP–GM, GW, GW–GM, SC-SM, SM	GP, GW, GP–GC, GP-GM, GM, GC, GW–GM, SP, SP–SM, SW–SM, SC
	Mode	CL	CL SM	GW–GM

kPa (median 120 kPa) in Zone 1.2 and between 60 and 300 kPa (median 250 kPa) in Zone 1.3.

The water table (Fig. 8) is located at shallower depth (about 0–2 m) in the Western sector of the Vega, near the main river courses, descending to depths of 150 m in the eastern and south-eastern sectors.

Some anomalies were observed during several geotechnical in situ studies concerning the measurement of water-table depths in drill holes compared to the available maps of water tables published by the Spanish Geological Survey (IGME-FAO 1972) and the Provincial Hydrogeological Atlas of Granada (DIPGRA-ITGE 1990). These depth anomalies were interpreted as resulting from:

a) Perched water levels in granular intermittent layers in cohesive sediments resulting at lower depths than expected in some areas of Granada, Cájar, Las Gabias and Maracena were the water tables appear in between 8 and 12 or 16–18 m.

b) Drought periods during which the depth to the water table may be higher than expected. Therefore, the standard index of rainfall drought defined by the Provincial Hydrogeological Atlas of Granada (DIPGRA-ITGE 1990) shows negative values resulting from cumulative low rainfall anomalies over the period; this index is applied to the assessment of water inflow into the regional aquifers for the period 1950–2011 (Junta de Andalucía 2011), e.g., between 1979 and summer of 1995, or summer of 1998 and winter of 2000, and even

between beginning of 2005 and 2008 and from May to November of 2009 rainfall largely decreased below the expected average. From these sorts of situations, the water table may reach 7 m or more below its theoretical position in Láchar, 6–10 m below in Pinos Puente, and 4 m below in Santa Fe and Chauchina.

Interpolation methods

The analysis was performed in ArcGIS 9.3 (ESRI 2009) using several interpolation methods: inverse distance weighted, global polynomial interpolation (order from 1 to 5), ordinary local polynomial (order from 1 to 5), radial basis functions, kriging (ordinary, simple, universal and disjunctive) and diffusion kernel interpolation. In all these interpolation methods, except inverse distance weighted (IDW) and radial basis functions (RBF), the initial values were in a zone created by the interpolation. This area has a greater or lesser value than the interpolated data. Furthermore, the discretization of areas was so large that important information was lost (Fig. 7).

To predict a value for any unmeasured location, IDW interpolation uses the measured values surrounding the prediction location. IDW assumes that each measured point has a local influence that diminishes with distance. IDW is an exact interpolator, where the maximum and minimum values in the interpolated surface can only occur at sample points. IDW assumes that the phenomenon being modelled
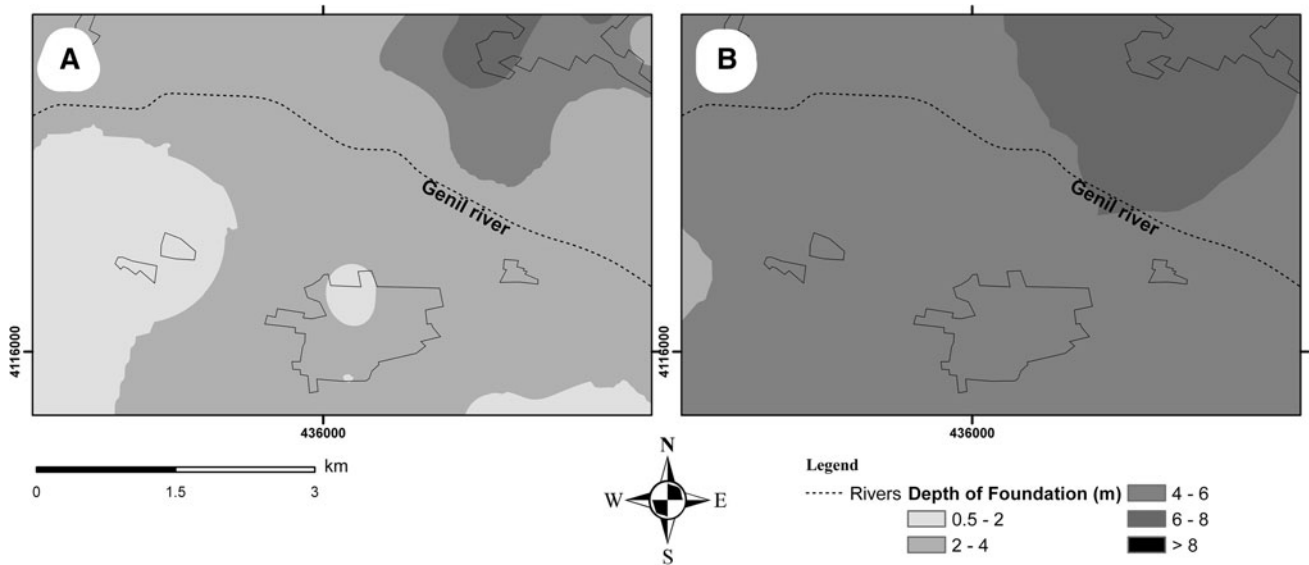
Fig. 7 Comparison of results of IDW interpolation (*left*) and disjunctive kriging (*right*)

Table 2 Root mean square prediction error (RMSPE) of bearing capacity, depth of foundation and N_{SPT} values obtained from different methods

Interpolation method	Order	Bearing capacity RMSPE	Depth of foundation RMSPE	N_{SPT} RMSPE
IDW	–	0.47	0.98	4.88
Global polynomial	1	0.56	1.33	6.00
	2	0.58	1.30	6.30
	3	0.59	1.29	7.15
	4	0.58	1.26	6.98
	5	0.58	1.25	7.08
Local polynomial	1	0.45	1.21	4.58
	2	0.45	1.22	4.79
	3	0.48	1.24	4.83
	4	0.56	1.24	6.74
	5	0.57	1.28	6.79
Radial basis functions	–	0.46	1.22	4.81
Kriging	Ordinary	0.92	0.89	0.92
	Simple	0.90	1.07	0.89
	Universal	1.03	0.89	0.92
	Disjunctive	0.88	1.09	0.88
Diffusion kernel	–	0.57	1.25	5.57

is driven by local variation, which can be modelled by defining an adequate search neighbourhood.

Global and local polynomial interpolations fit a smooth surface that is defined by a mathematical function (a polynomial) to the input sample points. While global polynomial interpolation fits a polynomial to the entire surface, local polynomial interpolation fits many polynomials, each within specified overlapping neighbourhoods. Global polynomial interpolation is useful for creating smooth surfaces and identifying long-range trends in the dataset. However, in earth sciences, the variable of interest usually has short-range variation in addition to long-range trend. When the dataset exhibits short-range variation, local polynomial interpolation maps can capture the short-range variation.

Radial basis function methods are a series of exact interpolation techniques. They are used to produce smooth surfaces from a large number of data points. The functions produce good results for gently varying surfaces such as elevation. However, the techniques are inappropriate when large changes in the surface values occur within short distances and/or when you suspect the sample data is prone to measurement error or uncertainty.

Kriging is an advanced geostatistical procedure that generates an estimated surface from a scattered set of points with z values. Kriging assumes that the distance or direction between sample points reflects a spatial correlation that can be used to explain variation in the surface. Kriging is the most appropriate method when there is a well known directional bias in the data. It is often used in soil science and geology; however, it is a very complex and multistep process.

Diffusion interpolation refers to the fundamental solution of the heat equation, which describes how heat or particles diffuse with time in a homogeneous medium. This technique is unsuitable for the available data.

The root mean square prediction error (RMSPE) quantifies the error of the prediction surface. RMSPE values show that the better methods showing lowest errors were the local polynomial (order 1) for bearing-capacity values, ordinary kriging for foundation-depth values, and disjunctive kriging for N_{SPT} values (Table 2).
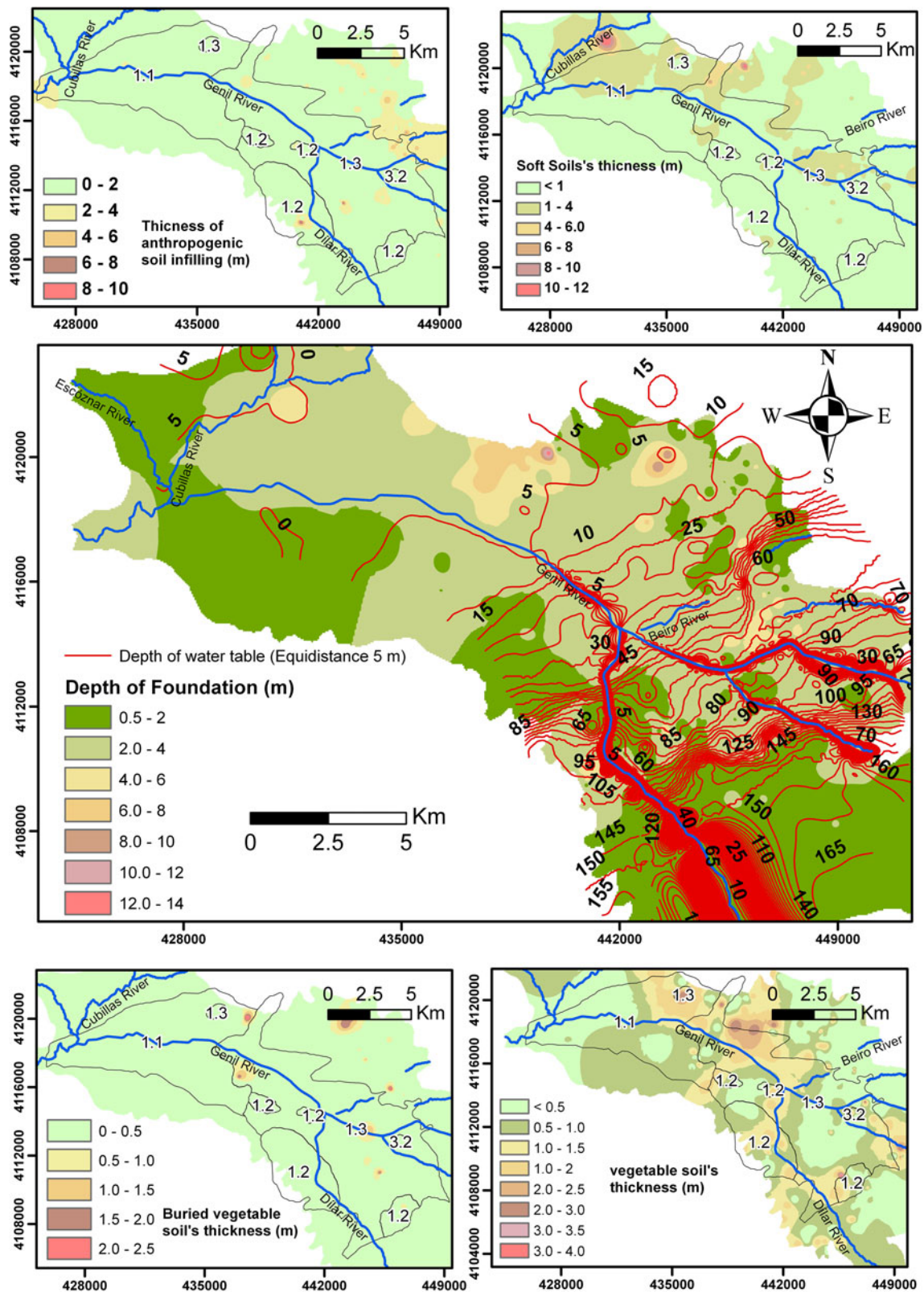
Fig. 8 Minimum depth to the foundation level from analysis of local bearing capacity and anthropogenic fill thickness, thickness of the top vegetable soil, and also buried vegetable soil below the anthropogenic soil infilling, thickness of soft soil with very low bearing capacity, including water table depth (bold numbers) (the alluvial soils are delimited by the continuous *black line*)

Table 3 Variation range observed for the following data: anthropogenic fill thickness, thickness of the top organic soil, organic soil below the anthropogenic soil infilling, thickness of soft soil with very low bearing capacity, water table depth, minimum depth of foundation, bulk density, cohesion, internal friction angle, N_{SPT} and bearing capacity

	Zone 1.1. Holocene	Zone 1.2.	Zone 1.3.
	Cohesive soil	Cohesive fine-granular soil	Coarse granular soil
Anthropogenic fill thickness (m)	0–3.5	0–9.5	0–5.0
Thickness of the top vegetable soil (m)	0–2.0	0–2.0	0–4.0
Vegetable soil below the anthropogenic soil infilling (m)	0	0–1.0	0–2.0
Thickness of soft soil with very low bearing capacity (m)	0–3	0–3.5	0–5.0
Water table depth (m)	0–8	0–150	2.5–150
Minimum depth of foundation (m)	0.5–3.5	1–9.5	0.5–8.0
Bulk density (KN/m^3)	18–20	18–20	18–20
Cohesion (KPa)	100–300	0–700	0
Internal friction angle (°)	20–24	20–36	30–36
N_{SPT}	5–20	8–30	15–50
Bearing capacity (KPa)	40–100	50–250	60–300

However, even though the IDW yields slightly higher RMSPE values than the other methods, this is an interpolation method in which the starting points maintain the value of the variable analysed, and no original information is lost. Therefore, the IDW was chosen as the interpolation method for bearing capacity and foundation-depth values given its relative simplicity, because it required fewer input decisions than the kriging method and no statistical requirements according to Watson and Philip (1985), Robinson and Metternicht (2006), and Rauch (2011). The lower RMSPE value for N_{SPT} data is obtained by disjunctive kriging, although, as it is discussed later, the predicted points show lower dispersion by IDW interpolation.

With the use of the Topo to Raster tool of ArcGIs 9.3 (ESRI 2009), a map of depth to the water table was drawn, with an interpolation method specifically designed for creating digital elevation models in hydrology, taking in account the distribution of drainage networks. (Hutchinson 1989, 1993; Hutchinson and Dowling 1991). This tool is able to perform data interpolation without losing the continuity of the surface being analysed, as frequently occurs in global kriging and spline-interpolation methods.

Results, discussion and conclusions

Results

This paper provides a description of a GIS approach to mapping the distribution of geotechnical parameters in a given region. The results are valuable for planning future urban growth in the study area and also as a model for future development in surrounding areas. The thicknesses of anthropogenic soil infill, vegetable soil, buried vegetable soil, and soft soils were taken into account when specifying

the minimum depth of the foundation (see Fig. 8 and Table 3), which was found to be 0.5–4 m. This study also found distinctive areas, such as the north-central area, having a six-meter thickness of soil with very low bearing capacity. The spatial distribution of geotechnical parameters showed a marked heterogeneity that ranged from fine to coarse alluvial soil. The water-table depth (Fig. 8; Table 3) progressively increased from NW to SE (0–40 m). In addition to this hydrological condition, there is also the fact that soils with poorer geomechanical parameters (Figs. 8, 9; Table 3) were located in the area where the water table was nearer to the surface.

Discussion

The available in situ geotechnical data (mechanical rotary drilling, penetration tests, sampling in percussion drilling, laboratory tests) were distributed mainly in the surroundings of growing urban areas of each municipality where the construction of new buildings was allowed. Also a number of geotechnical reports were made for linear public works in areas outside of the urban centres.

Nevertheless, a lack of information in the central and central-western area of the Vega contributed to the increase in RMSEP values in different properties, which could be reduced in the future by gathering new geotechnical data from in situ tests in these areas.

Concerning the interpolation methods, those with better RMSEP values are IDW, local polynomial, and disjunctive kriging, although in the 20 random control points, the predicted points show better adjustment by IDW interpolation (Fig. 10), even with lower RMSEP, than local polynomial and disjunctive kriging for bearing capacity and N_{SPT}, respectively. The same results hold for the other geotechnical parameters.
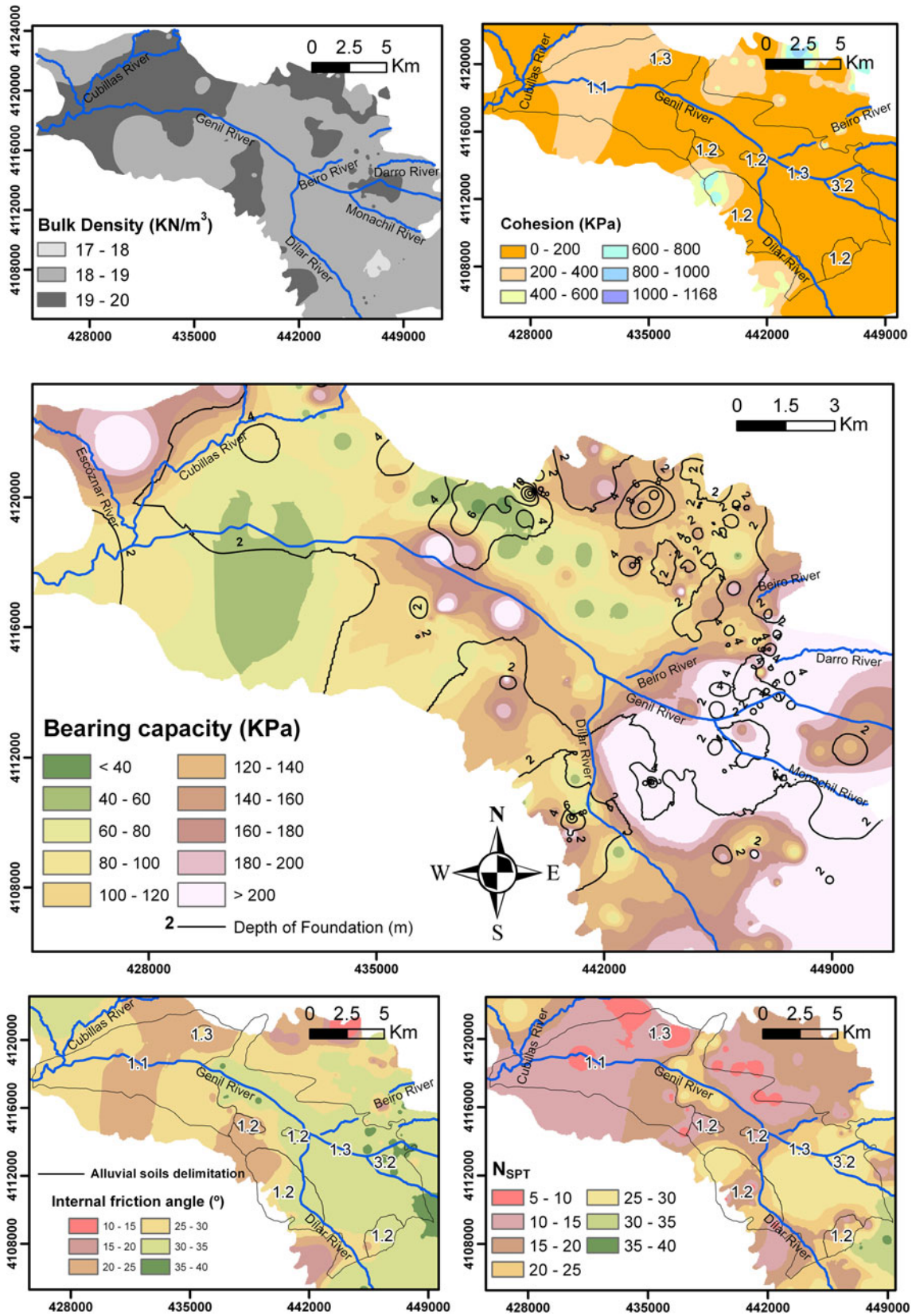
Fig. 9 Spatial distribution of bearing capacity including minimum depth to the foundation level (contour map and bold numbers), bulk density, cohesion, internal friction angle, and N_{SPT} value (the alluvial soils are delimited by continuous *black line*)
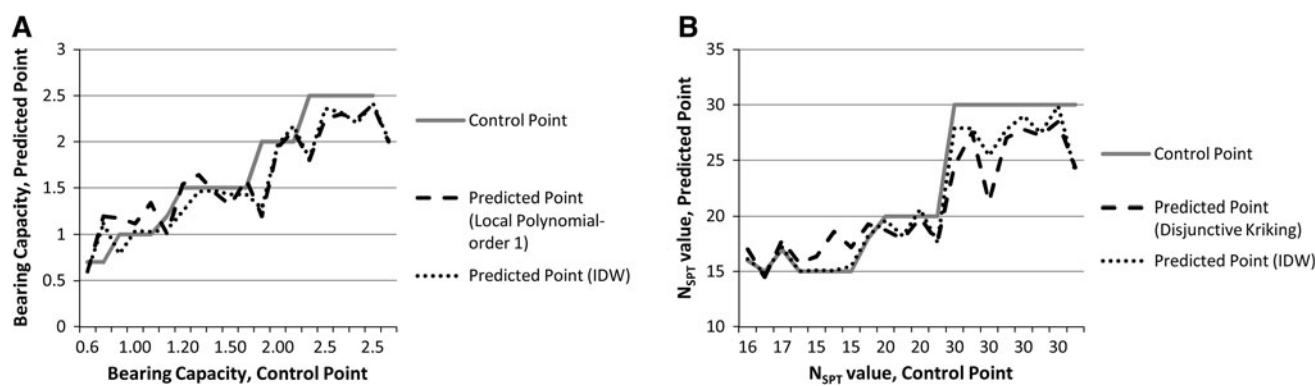
Fig. 10 Graphical pictures to compare predicted point and control point for bearing capacity (a) and N_{SPT} (b) in two interpolation methods

The geotechnical parameters established appear with an irregular spatial distribution in the alluvial Holocene deposits related to three zones comprising 14 municipalities of the metropolitan area of Granada (Spain). As the basic geotechnical information is directly related mainly to building projects, the resulting maps show higher accuracy in urban areas than in the surrounding rural land, where the geotechnical projects are less abundant, especially among the more distant municipalities; clearly, the geotechnical information remains reliable also in smaller areas between closer municipalities such as Granada, Maracena, Pulianas, Armilla, Churriana de la Vega.

The density of the statistical population, considering only the number of data at the foundation level and close around, is homogeneous and limited to 5 ± 3 samples, so only the variation percentage of standard deviation respect to mean and median would be useful to decide which parameters have better spatial coverage. According to this criteria, density, internal friction angle have a small variation (<5 %). On the other hand, Cohesion and N_{SPT} are necessary to evaluate the ultimate bearing capacity (according to Terzaghi 1943; Meyerhof 1963; Hansen 1970; Schmertmann 1975) although their percentage of variation ranged between 15 and 50 %.

The geotechnical information shown in these maps cannot replace a building geotechnical report, which is obligatory in all Spanish civil engineering or building projects. This means that these maps constitute an important tool for future urban planning, but are not intended for replacing the obligatory local geotechnical surveying.

Currently, there is no other source of geotechnical information except for a General Geotechnical Map of Spain (1:200.000) published by the Spanish Industry Ministry four decades ago and without any geotechnical data, and some unpublished Geotechnical Maps for Urban Planning (1:25.000) in cities of Spain published by Ministry of Industry and Energy-Geological and Mining Institute of Spain (IGME) three decades ago, with much less data and very imprecise differentiation of geotechnical zones.

Conclusions

After an error analysis of different ArcGis 9.3 (ESRI 2009) based interpolation methods, the best-fitted method, IDW, was used to establish the spatial distribution of the available geotechnical and soil-unit data: anthropogenic fill thickness (from 0 to 9.5 m), thickness of the top vegetable soil (from 0 to 4.0 m), vegetable soil below the anthropogenic soil infilling (from 0 to 2.0 m), thickness of soft soil with very low bearing capacity (from 0 to 5.5 m), depth to water table (from 0 to 150 m), minimum depth to foundation level (from 0.5 to 9.5 m), bulk density (from 18 to 20 KN/m^3), cohesion (from 0 to 300 kPa), internal friction angle (from 20 to 36°), N_{SPT} (from 5 to 50) and bearing capacity (from 40 to 300 kPa).

Some areas have low density of data in the central and central-western Vega, where urban areas are scarce and therefore there is a lack of geotechnical reports for building foundations or civil-engineering projects, the only sources of the available geotechnical data. A further significant reduction of the RMSEP values found, and a better correlation between data from control and predicted points, could be attained in the future if new buildings or civil engineering projects in these areas supply the necessary geotechnical data. The results in this study can be used to assist urban expansion and development processes. The method described is also valid for general planning, although it may be less useful on a local scale, on sites where geotechnical heterogeneity is higher.

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