



# Urban geology from a GIS-based geotechnical system: a case study in a medium-sized city (Oviedo, NW Spain)

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## Abstract

This paper describes the development of a GIS-based geotechnical system designed to face challenges on urban geology in a Spanish mid-sized city. Its multipurpose nature is based on a relational database that holds a wide variety of georeferenced ground data, mostly extracted from geotechnical reports or acquired during fieldwork. At present it includes, among other unpublished information, more than 2000 site investigations and the results from 5000 tests carried out on rock, soil and groundwater samples. This desk tool provides a better understanding of the bedrock and superficial geology through the spatial analysis of the collected subsurface data. The main achievements include the classification and mapping of man-made grounds, fluvial sediments and residual soils; the identification of unreported faults; the review and detailed study of geotechnical parameters and properties of the rocks and soils; and the hydrogeological characterization of the permeable units. It also provided the surface geological mapping of the urban area; the development of a geo-engineering map based on lithological, geotechnical and construction criteria; and the creation of a preliminary 3D layer-based ground model of the city centre, where the subsurface contains stone used for heritage buildings listed by UNESCO.

**Keywords** Database · Engineering geology · Geographic information system · Oviedo · Urban geology

## Introduction

Databases implemented in Geographic Information Systems (GIS) are an efficient way to manage geographically referenced data. They present well-known advantages for handling of ground investigation data, providing a wide range of functionalities. For instance, GIS enables capturing and integrating a great variety of information gathered from unrelated sources. The geodata are usually incorporated into a multilayered database, sharing a common spatial referencing system, allowing data from various sources to be easily manipulated, updated or shared through Web-based systems (Chang and Park 2004; Kunapo et al. 2005). Spatial and non-spatial queries are performed in the databases,

and GIS software has significant spatial analysis capabilities such as geoprocessing tools. The data might be shown in a number of ways, including 3D modelling and visualization, both important research topics of modern geology (Culshaw 2005).

GIS is widely used for thematic mapping related to natural hazards such as landslides (e.g. Chacon et al. 2006), earthquakes (e.g. Chung and Rogers 2010), karstified areas (e.g. Yilmaz 2007; Galve et al. 2009), liquefaction potential (e.g. Kolat et al. 2006), volcanic areas (e.g. Alberico et al. 2005), or coastal management (e.g. Debaine and Robin 2012; Flor-Blanco et al. 2015; Domínguez-Cuesta et al. 2015) and climate change (Aranda et al. 2020; Simonovic 2017). These maps help public administrations to optimize regional and local development; they facilitate the selection of suitable sites for housing and infrastructure construction from the geological viewpoint; and improve the design of ground investigations for engineering projects. There is a greater awareness of the importance of inputting field data into digital databases (Culshaw et al. 2006): for example, the national geotechnical databases developed by some European geological surveys (e.g. BGS, GSI, IGME, TNO) which contain thousands of survey sites. This preserves the

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results of the investment fieldwork and laboratory tests that might be lost in the future. The storage within relational databases is the most common and, currently, the best option (Veeger et al. 2004).

At the urban scale, GIS-based technology addresses the need to store and manage ground data, especially in metropolitan areas where the construction of large infrastructure provides a wide range of new subsurface data (e.g. tunnelling). Thus, the databases are becoming increasingly more important in the management and visualization of geotechnical data (Orhan and Tosun 2010; Wan-Mohamad and Abdul-Ghani 2011), which is enhanced by the software improvements (Chadwick et al. 2006). Therefore, they are very useful tools for geo-engineering and geo-environmental evaluation related to urban planning and redevelopment of brownfield sites (Dai et al. 2001).

A brief overview of trends in urban geology and databases illustrates the broad field of interests for geologists and engineers, among others: geological setting (structural contour maps and 3D subsurface models), hydrogeological research (groundwater flow trends, water quality and spreading of pollutants), hazard management (e.g. expansive soils, natural or man-induced subsidence), geo-engineering zoning (i.e. mapping of geotechnical properties and constructive conditions), and more recently the analysis of the effects of climate and future climate change. In Europe, there are among others, GIS-related research projects and databases at urban areas from countries such as Austria (Pfleiderer and Hofmann 2004), Belgium (Devleeschouwer and Pouriel 2009), UK (Ford et al. 2008; Royse et al. 2009), Finland (Vähäaho 1998), France (Marache et al. 2009; Thierry et al. 2009), Germany (Neber et al. 2004; Neumann et al. 2009), Greece (Koukis and Sabatakakis 2000), Italy (Rienzo et al. 2009; Ciotoli et al. 2015), Norway (De Beer et al. 2012), Portugal and Scotland (Campbell et al. 2010). The integration of subsurface urban environment in land-use planning and management was investigated and promoted by the COST Sub-Urban project, a European network involving geological surveys, local authorities and research partners (Campbell et al. 2014). In general, geotechnical databases have been produced in cities with large metropolitan areas, but some are national.

In this case, the aim is the creation of a GIS-based geotechnical information system designed to provide geological and geotechnical information for a medium-sized Spanish city. The development of such tools has reported good results in other cities (e.g. Entwisle et al. 2016). Oviedo has an important architectural heritage dating back to the ninth century that must be protected when infrastructure is built in the vicinity. It includes monuments listed as UNESCO World Heritage Sites, and more than 20 buildings that are declared Sites of Cultural Interest, the highest protection in the Spanish Historical Heritage Law. However, the

geological and geotechnical features of the urban subsurface determine changing conditions for excavation and foundation works, which, in some cases, have led to severe structural damage and with economic consequences (e.g. Gutiérrez Claverol et al. 2004; González-Fernández et al. 2010).

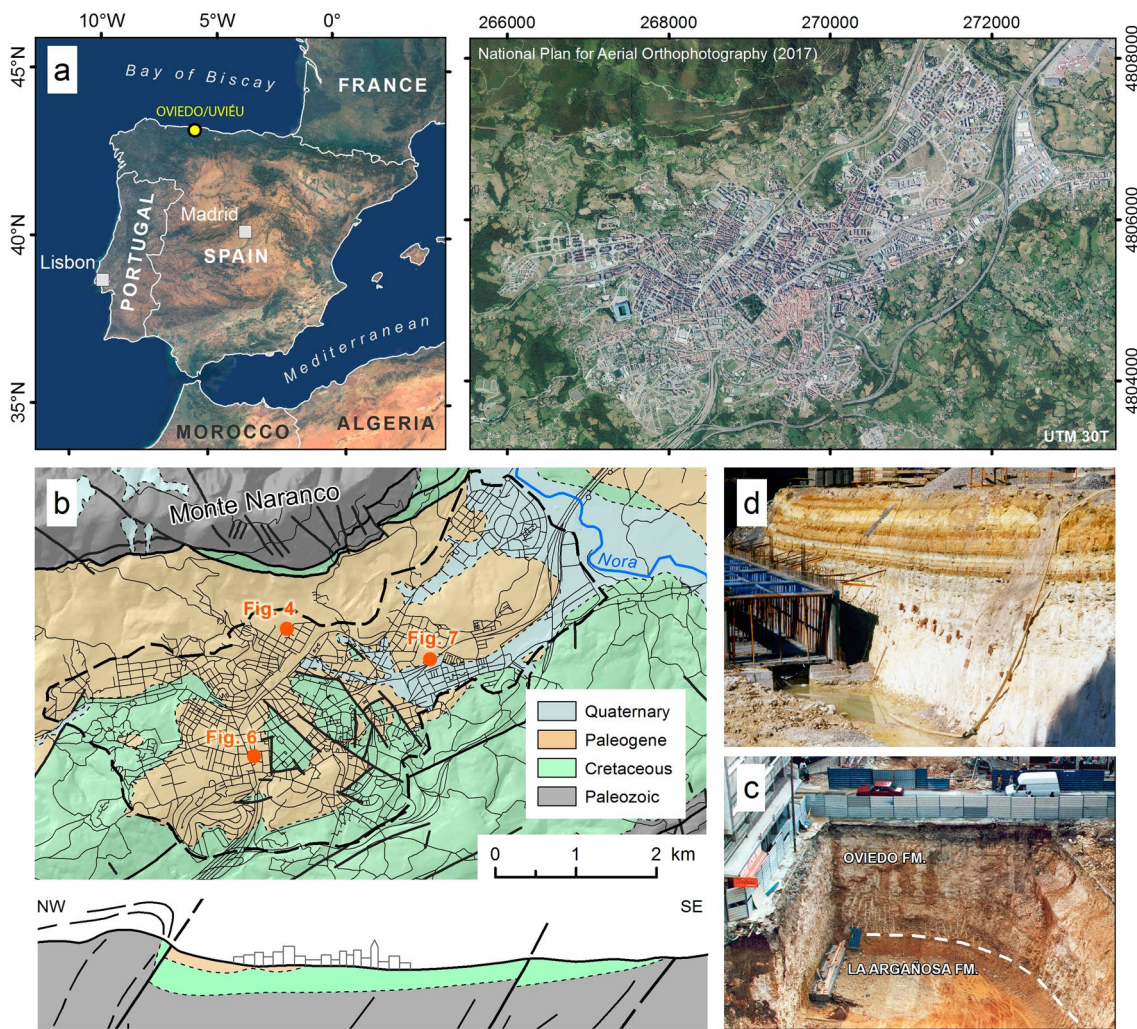
This research focuses on addressing some unresolved challenges of the subsurface of Oviedo, which responds to local needs, from the management of ground data stored in a digital database. This means paying closer attention to: (i) the Quaternary deposits, which are more permeable, weaker, and have lower bearing capacity than the bedrock, and whose mapping has been incomplete due to the absence of outcrops; (ii) the characterization of karst phenomena in carbonate rocks and gypsum, which cause construction issues; (iii) the investigation of faults in the built-up area, as the distribution is insufficiently known; (iv) a better understanding of underground water flow and the potential interaction with the construction of infrastructure; (v) a detailed analysis of the main geotechnical properties of rocks and soils, to assist geotechnical investigations related to civil engineering and building projects.

## Study area

Oviedo/Uviéu is the capital city of the Principality of Asturias and its population is around 215,000. The urban centre, situated 350 km north of Madrid (Fig. 1a), covers an area of 15 km<sup>2</sup>. The city is built on an undulating topography where slope angles are commonly 5° and locally as high as 15°, while the elevations—from NE to SW—range between 160 and 330 m above sea level (Fig. 2). To the north of the urban area, the relief is more rugged and the highest elevations are over 600 m.a.s.l.

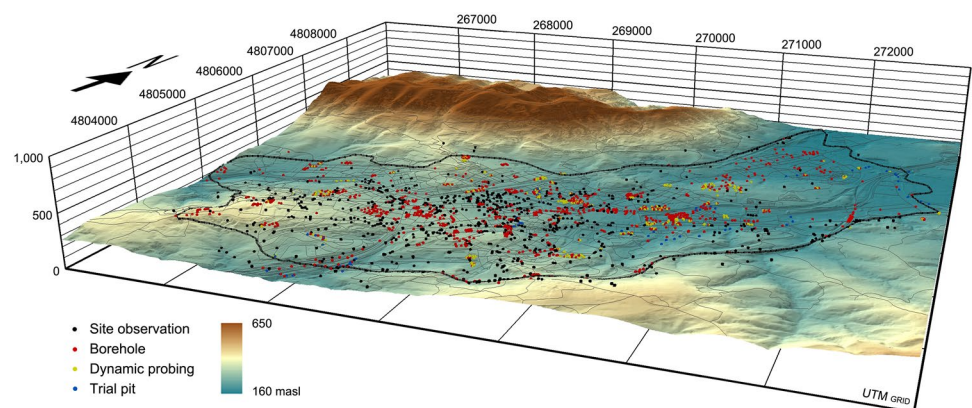
The city is on sedimentary rocks of Mesozoic–Palaeogene age. The rock sequence forms parts of a basin gently folded in an ENE–WSW oriented synclinal structure (Fig. 1b), resting nonconformably on the basement of strongly folded Devonian and Carboniferous formations. The Cretaceous series consists of alternating carbonate and siliciclastic units (González Fernández et al. 2004), two of them outcropping in much of the urban area: the La Argañosa Formation and the Oviedo Formation (Fig. 1c). The former, below, is a succession mostly composed of sands that constitute an important regional aquifer, and the latter, above, corresponds to yellowish-brown limestone affected by karst producing a varied palaeorelief. Below the two Cretaceous units is the San Lázaro Fm., comprising carbonate rocks (Table 1). This unit occurs near surface and some geotechnical ground investigations reach it. In the unconformable Paleogene series of fluvial–lacustrine origin, three major lithological units were identified (Gutiérrez Claverol and Torres Alonso 1995):





**Fig. 1** a Location of the study area; b simplified geological map and cross section of the Oviedo basin; c Cretaceous formations at the urban subsurface; d excavation in lacustrine limestones of Paleogene age

**Fig. 2** Distribution of site investigations in the study area



the lower one is mainly composed of marl and limestone layers (Fig. 1d; the middle unit consists mostly of marly clay; and clay and sand deposits dominate the upper unit. Finally, the Quaternary is mainly represented by fluvial

sediments (a rooftop sequence of gravels, sands and clays) linked to the Nora River in the northeaster margin of the city, and other minor deposits related to ancient streams

**Table 1** Main pre-Quaternary geological units forming the urban subsoil

Age	Name	Thickness (m)	Main lithologies
Paleogene (Eocene - Oligocene)	Upper unit		Clay, sand, layers of marl and sandstone
	Middle unit	> 200(whole Paleogene)	Marly clay, marl, clay layers
	Lower unit		Marl with limestone layers, intercalated gypsum and clay layers
Upper Cretaceous	Oviedo Fm.	0–15	Limestone, sandy limestone, layers of calcareous sandstone
	La Argañosa Fm.	40	Sand, intercalated clay and gravel layers
	San Lázaro Fm.	40–50	Limestone, sandy limestone, marl, layers of clay and sandstone

and small lakes obscured during urban growth, obliterating the geomorphological evidence of their existence.

The structures in basement rocks reflect the deformation that occurred during the development of the Variscan belt, an orogeny that in the Iberian peninsula was mostly active during the Carboniferous (e.g. Pérez-Estaún et al. 1991). The faults and folds (Fig. 1a, b) affecting the Mesozoic and Palaeogene rocks relate to the formation of the Cantabrian Mountains during the Paleogene, as part of the Alpine belt in north Iberia. The Alpine convergence involved major steeply dipping reverse faults and minor steeply dipping subvertical faults, trending either NW–SE or SW–NE, some of which reactivate previous Variscan thrusts (Alonso et al. 2009). The Monte Naranco hill, to the north of the city, constitutes the hanging wall of an east-oriented reverse fault (Fig. 1b). The landscape and the geomorphology of the area are dominated by fluvial processes, but has been greatly altered by human activity in some parts of the city. In fact, the natural erosion of the tectonically uplifted block to the north of the city has been obscured by the earthmoving works during the northward expansion of the city, as will be seen later. Other currently active natural phenomena with impact on the geotechnical characteristics of sedimentary rocks, such as the dissolution of carbonate rocks and gypsum resulting in the formation of karstic features, are concealed in the built-up area below residual soils, fluvial deposits and man-made fills.

## Methodology

### Data and information collection and addition to the GIS

Two types of geological information were compiled: data obtained during this research and data supplied by external sources. The first consisted in fieldwork, oral communications and site visits to building works (excavation and foundation stages) and other construction works including pipe burial or pavement renewal. It involved the examination of more than 700 sites (Fig. 2) and more than 2000 photographs. The secondary data came from dissimilar storage

systems and formats (hard copy documents, computer file, etc.). More than 400 documents from the past 60 years were collected (Table 2). Private consultants and contractors provided most of them, which were reviewed with confidentiality requirements. Additional data about the subsurface were obtained from public and private archives, public libraries and local newspapers' libraries. A wide range of multiscale maps were also compiled to provide spatial support to the subsurface data. Survey authorities such as the National Geographic Institute, the Geological and Mining Institute of Spain, the Principality of Asturias Government, and the City Council provided the documents. Around 270 maps and images were stored in either vector or raster formats with scales varying between 1:25,000 and 1:1000 (Table 2). Since their varied origin and wide variety of scales and updates, different types of checks were performed to ensure their quality and spatial consistency and compatibility. The corrective measures applied depending on the case were assignment of the geodetic system, projection transformations and georeferencing.

A GIS-based relational database was then designed using ArcGIS Pro v. 2.7 (from ESRI). This software provided the necessary capabilities: standardized input and integration of multidisciplinary geodata; storage, manipulation and retrieval of data; content updating; analysis and processing tools; and varied graphical outputs. All the geographic items and geodata must have an unequivocal spatial location ( $X, Y, Z$ ) within a common frame of reference, so geodesic datum and the Universal Transverse Mercator grid system were selected. The content, i.e. ground data, was mainly provided from ground investigations. Boreholes and dynamic probing location plans were usually available in hard copy format, so more than 250 paper maps without grid references were scanned and georeferenced. The procedure was based on image rectification of the location plans through rubber-sheeting process using checkpoints on vector-based maps. Thereby, more than 1500 site investigation points were spatially located with the highest possible planimetric precision (Fig. 2). This consisted of 1159 rotary drill holes providing 18,800 m of logged material; 68 trial pits with average depth of 3.3 m; 315 super heavy dynamic probing (DPSH) and other probing tests representing more than 2 km

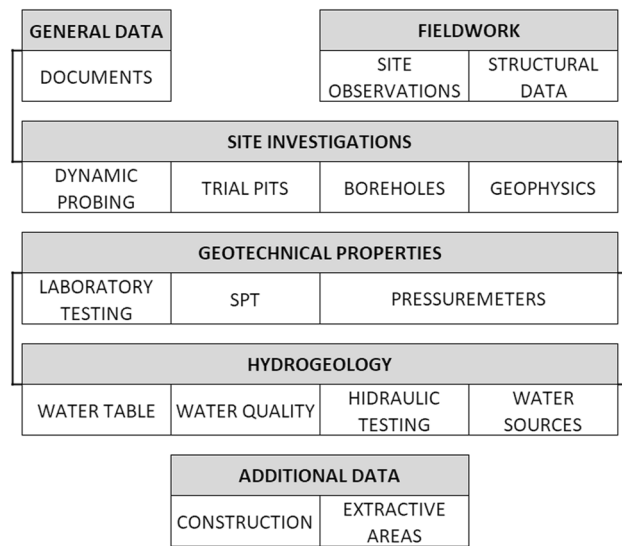


**Table 2** Main sources of ground data and geographic resources

Documents providing ground data	Geotechnical reports	Building and single-family housing construction, urban planning, land management units, residential polygons, urban development
	Project reports for transport networks and urban services	Road works, railway facilities, sewers and water collectors, canalization of streams
	Project reports related to other urban infra-structures	Underground parking lots, sports facilities, shopping centres, educational institutions, health centres, water tanks
	Varied	Drilling of water wells, archaeological monitoring reports, slope stability analysis, expert opinions, special foundation works
Geographic data and thematic information	Cartography	Topographical maps; geological, hydrological and geomorphological maps; urban-specific documents as the cadastral map, historical city maps, street maps, urban development plans, etc.
	Imagery	Ortho-rectified aerial images, oblique aerial photos
	Digital Terrain Models	Digital Elevation Model, slope and hillshade maps

of penetration recording in soils and very weak rocks; 30 geophysical surveys using seismic refraction, electric techniques (vertical electrical sounding, electrical profiling and electrical resistivity tomography) and ground penetrating radar. The results of field and laboratory testing were also obtained from the documents. This included 1128 on-site tests (standard penetration tests, pressure meters and permeability tests) and laboratory testing over 1634 disturbed and undisturbed samples of rocks and soils and groundwater samples. Only those tested according to Spanish (UNE and NLT) and ASTM standards were selected. This produced directly around 4000 geotechnical values.

A good knowledge of the local geology is essential to distinguish the information extracted from geotechnical reports that are integrated within the database, and it is critical to identify data inconsistencies. This required defining at first a representative stratigraphic column of the near surface geology (general vertical section) based on Gutiérrez Claverol and Torres Alonso (1995) and then a careful check of the boreholes' log description and the corresponding core images. The geological attribution was carried out by a local geological expert. This enforced the lithostratigraphic consistency in the database. Moreover, ground data without reliable local location data, or with confusing data (e.g. borehole starting height inconsistent), were discarded. Unfortunately, no data were available in a digital data transfer format. Then, the data tabulated in GIS software were grouped into six thematic sections formed by feature classes and non-spatial tables (Fig. 3), which contain one or more common key fields to link the data: (i) general information about the compiled documents; (ii) general data about the site investigations indicating the thicknesses of the geological units identified in each prospection; (iii) location of water sources, depth to groundwater, hydraulic testing and water quality (sensory properties, physicochemical parameters, ion concentrations, bacteriological content and chemical corrosiveness



**Fig. 3** Schematic structure of the database

according to the Spanish code on structural concrete); (iv) geotechnical properties from field and laboratory tests (e.g. weight–volume relationships, soil grain size distribution, Atterberg limits, chemical testing, soils classifications, corrosivity, mechanical properties, abrasivity, etc.); (v) additional data related to construction works and information about extractive activities. Currently, the tabulated information exceeds 41,000 cells.

**Data analysis**

**Quaternary deposits**

The geometry of artificial grounds was evaluated from landscape transformations that occurred during the period of greatest expansion of the city (e.g. Luberti 2018), not

by borehole log-based interpolation of the basal surface of the anthropogenic deposits. The topographic data were derived from 1:5000 scale city maps. Digital elevation models (DEMs) were constructed from the contours and spot heights of the city maps that dated from 1869 to the present. Altitude deviations were checked against control points whose elevation has remained constant; and subtraction operations between DEMs were carried out. The fluvial deposits were mapped from the reconstruction of the hydrographic network now masked below the built-up area. The fluvial network was identified from historical maps and other documents (e.g. Lucchesi and Giardino 2015). From 14 topographic maps dating from the mid-nineteenth century to 2003, the distribution, profile and temporal evolution of the main streams were analysed. Once the configuration was known, it was used to select the geological survey points within the database that are closer to the natural stream distribution, to inform the boreholes to be used to identify the distribution and characterize the fluvial deposits.

### Faults

One of the main uncertainties about the subsurface in Oviedo has been in identifying faults. It is well known that the absence of direct observations often restricts the number of faults represented on geological mapping of cities (e.g. Aldiss 2013). The method used in Oviedo to identify the presence of faults consisted of interpolating the conformable contact between Oviedo and La Argañosa formations (Fig. 1c) from borehole data, analysing its spatial variations in depth. The procedure was first carried out at basin scale to detect the larger faults. This involved 160 borehole data around the basin. Through local polynomial interpolation, the stratigraphic boundary was identified from which a slope map was also produced. To assess the orientation and inclination of this lithological boundary, this surface was compared with almost 200 measures (dip and dip direction) taken of the bedding plains of the Oviedo Formation. At the urban centre, spatial analysis was conducted to identify faults with less vertical displacement in areas with high density of borehole data. The procedure was based on trend-surface analysis adapted from Mei (2009). It allows the separation of local features with respect to regional component when investigating the structural setting. The trend modelling was performed under local polynomial regression, and after analysing the residual data, inverse distance weighting (IDW) and kriging were applied to create the best-fit surface in each specific study area.

### Hydrogeology

Groundwater has caused problems in excavations (e.g. unexpected flooding in excavations or unstable slopes). Also, the

area has a relatively high annual rainfall (mean 1025 mm/year between 1976 and 2020), which contributes to a significant water recharge. Thus, the investigation of the main permeable units involved: ranges of hydraulic conductivities (estimated from field and laboratory data); sources of recharge; the depths of perched and the main water table; groundwater flow paths; chemical characteristics; and corrosion potential for structural concrete.

### Geotechnical data

Based on the results of field and laboratory tests, the identification, physicochemical and mechanical parameters collected were analysed using methods for instance percentiles plotted in box and whisker plots. The main properties that define the mechanical behaviour were also studied for each geological unit to complete the geotechnical assessment: plasticity, strength, stiffness, consistency, compressibility, expansivity and collapsibility. Properties such as plasticity required a specific style of plot. In several cases, it included assessing the variation with depth below ground surface of the parameters and properties.

### 3D model

The geological setting of the city centre was preliminarily virtualized through a 3D layer-based model. The upper surface was provided by a digital elevation model (2 m cell size) generated from 1:1000 topographic mapping and LiDAR data. The boundaries between geological units (Cretaceous formations, Paleogene and man-made fills) were interpolated by radial basis functions from the data provided by the boreholes.

## Results and discussion

The preparation of the database was conditioned by many factors. When entering data from multiple sources, most difficulties arise regarding the interpretation of the reviewed information, which differs in origin, quality or resolution. Thus, the nature of the input data was particularly heterogeneous given that much of the information came from geotechnical reports, some produced more than 30 years ago. Another constraint was the availability of new data, as it is difficult to ensure continuity in the input of information. Currently, the database is maintained and updated by the researchers from the University of Oviedo. For the moment, the tool is not publicly accessible, and it has been used exclusively for research purposes. In any case, it was possible to achieve a good spatial distribution of site investigations, and to recover and exploit many ground data that might be lost. The structure of the database, which is neither

advanced nor complex and which will be improved in the future, allowed the different spatial analysis procedures to be carried out. As planned, the processing of the collected geodata led to study separately specific challenges on the urban geology, as discussed below.

### Artificial grounds

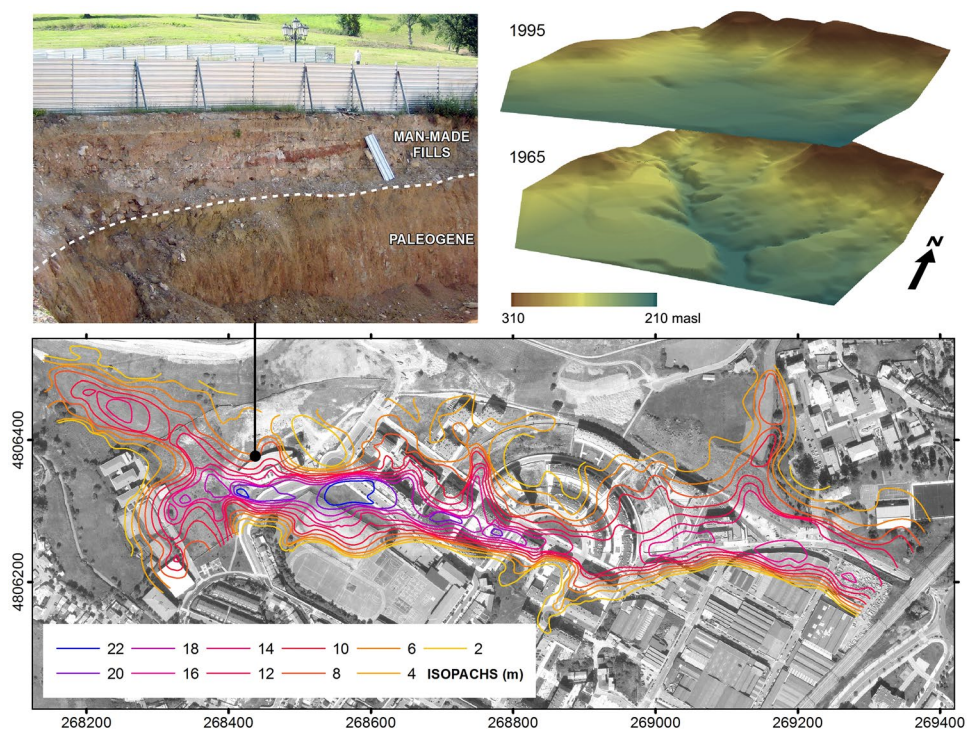
The results of the map algebra showed the ground elevation gains and losses occurred during different periods of urban development. This information was then combined with historical land uses, through the interpretation of aerial photography and the revision of old maps. After that, a review of more than 950 borehole logs was conducted for the identification of man-made grounds with a varied lithology, consistency and density, and an average thickness of 1.9 m (median of 1.2 m and maximum value of 25 m). Man-made ground was then mapped and classified into four categories according to their origin: (i) earthworks related to urban development; (ii) ground modified by civil engineering projects; (iii) ground modified by quarrying activities; (iv) dumping sites. The areas most transformed for each category were analysed in detail using DEMs with even higher resolution and quality to generate more accurate isoline maps of excavated and filled areas (Fig. 4). These models were validated using borehole data, achieving good fit between the thicknesses estimated beneath map algebra and those provided by borehole logs.

An important contribution was the identification of fills and voids related to old quarries, which have now disappeared because urban development took over these areas and integrated them into the city. Their geographic delimitation showed significant changes of the relief caused by the extractive activities (mainly quarrying limestone, sand and clay). The extent of some quarries, abandoned for hundreds of years, was identified during fieldwork (Gutiérrez Claverol et al. 2012). Although there was documentary references about them since the thirteenth century, no previous cartographic data on their location or extension in the historical archives were found. They had great historical significance, supplying building stone for monuments some of which are UNESCO World Heritage Sites.

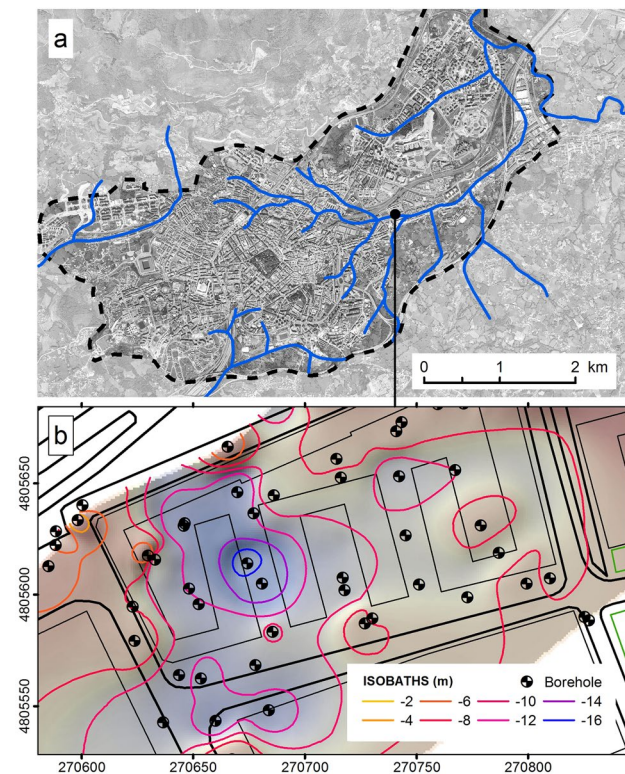
### Fluvial deposits

From the above-mentioned procedure, the first reconstruction of the old hydrographic network in Oviedo was obtained (Fig. 5a). This led to identify fluvial deposits in 282 boreholes, showing these sediments to have an average thickness of 4.7 m and a maximum value of 14.7 m. Then, isopachs and depth-to-bedrock maps were interpolated by IDW in areas with major accumulations of fluvial deposits. This procedure not only provided their extent and geometry, but also served to identify residual soils previously mapped as fluvial sediments. They are sometimes confused with highly weathered carbonate rocks (e.g. sand associated with weathering of Cretaceous limestone). For the above reason

**Fig. 4** Example of recognition of an old dumping site; an ancient stream valley filled for 30 years with demolition and construction wastes. See location in Fig. 1





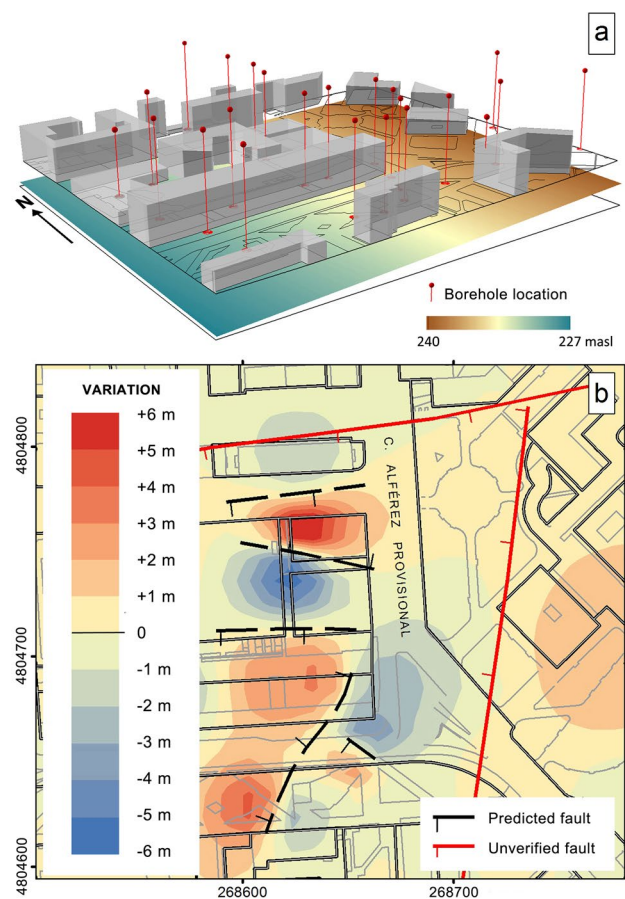


**Fig. 5** **a** Distribution of the hydrographic network in the mid nineteenth century overlapping a recent orthophoto; **b** depth of a karstified gypsum bedrock under fluvial deposits, in which depressions are sometimes linked to buried sinkholes

and given the absence of outcrops, the correct mapping of Quaternary deposits within the urban core has always been difficult. Because of the above, it was possible to classify correctly the nature of some soil samples collected that had been interpreted as being of fluvial origin when they were added to the database. This was essential to improve the study of the geotechnical properties of the Quaternary cover. Moreover, and as a complementary result not previously expected, some accumulations of fluvial sediment revealed to form the fill of buried sinkholes (Fig. 5b). This is important because these features are karstic subsidence phenomena (Pando et al. 2013).

### Fault identification

The spatial analysis procedure revealed basin-scale outliers, as abrupt inflections of the interpolated surface and identified much higher than the usual dip range for Cretaceous units ( $5^{\circ}$ – $15^{\circ}$ ). These anomalies have been interpreted as possible faults due to their linear patterns, and the directions are also consistent with the NW–SE and NE–SW trends of well-known dip-slip faults in the basin (Juilvert and Marcos 1973). Their vertical displacements have been calculated



**Fig. 6** **a** Regional trend for the geological boundary between the Cretaceous formations under several buildings; **b** altitudinal deviations of the trend caused by local features at the same area. See location in Fig. 1

to exceed 10 m. Furthermore, examining the cartographic extension of several of these faults outside the main urban centre (where there are no Cretaceous formations), they are compatible with the layout of Variscan faults affecting the Palaeozoic basement. This supports the hypothesis that the Alpine orogeny reactivated these previous faults according to Alonso et al. (1995).

The study of the local trend of the Cretaceous contact in areas of the city with a high density of boreholes (Fig. 6a) proved useful to search for faults with less vertical displacement. After refining the results by cross-validation and after being reviewed by a geologist, some of the fitted surfaces showed anomalies likely caused by faulting not previously mapped (Fig. 6b). As with the procedure applied to the basin, some faults already mapped were verified, but others were not as no vertical displacement of the presumed fault plane was identified. The results were promising, but they should be used with caution, since the representativeness depends largely on data density, the spatial distribution of boreholes and the method of modelling. The presence of

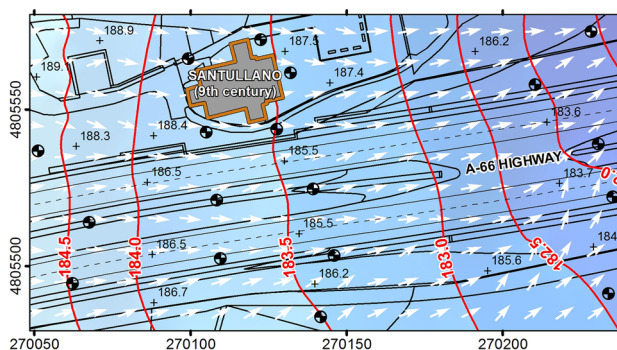


some of the faults were tested by the changes in thickness of the Paleogene that were interpreted as caused by faults in previous maps (Beroiz et al. 1973; Martínez-Álvarez et al. 1975). Since no faults have been identified, they are probably related to the irregularity of the palaeorelief of the Cretaceous formations.

## Hydrogeology

In Oviedo's subsurface, there are both geological units that are exploitable aquifers, and units with very low overall permeability but which occasionally have interbedded water-bearing layers. In relation to the most permeable units, the La Argañosa Fm. forms a multilayer of aquifers (when sand predominates), aquitards (fines content over 40%) and aquicludes (clay layers) whose thicknesses rarely exceed a few meters. Piezometric contour maps led to the identification of the preferred paths of the groundwater flow, toward the ENE under the urban area, which is consistent with the trends predicted at basin scale (González Fernández et al. 2005). Figure 7 shows an example of such a trend, estimated in this area from this research using piezometric data from a highway burial project. In the case of Oviedo Formation, the detailed review of borehole logs and piezometric data led to the local identification of hydraulic independence with the aforementioned multilayer system, due to low permeability clay layers and carbonate-cemented microconglomerates at the top of La Argañosa Fm.

The fluvial-lacustrine series has usually been interpreted as forming an aquiclude that overlies the Cretaceous aquifers; in fact, permeability values are as low as  $10^{-11}$  m/s. However, this research highlighted three geological settings with hydrogeological importance: (i) a karstic aquifer related to gypsum located in the north-eastern part of the city, sometimes confined, with a very high sulfate content (occasionally over 1 g/l); (ii) aquifers linked to sand layers or marl beds partially decalcified by weathering; (iii) circulations



**Fig. 7** Trend of the underground flow data within a sandy aquifer below a pre-Romanesque church at the NE part of the city. See location in Fig. 1

through karst conduits and fissures in the rock mass. The location of sulfate-rich groundwater was also used to inform the distribution of gypsiferous layers.

## Geotechnical properties

The analysis of geotechnical parameters and properties produced reference values (typical, extreme...) for each geological unit, as well as guidelines on the geotechnical behaviour of the different geological units and their lithologies. The availability of this information will be useful for future studies in the city. However, a further contribution has been the review of the lithological variations within the Paleogene deposits. The great lithological variability and the scarcity of outcrops complicate the grouping of materials into homogenous geological units; this key issue was recurrent in previous studies (e.g. Truyols Santonja and García-Ramos 1991). The mechanical behaviour also varies (e.g. uniaxial compressive strength ranges between 80 kPa to 120 MPa). However, in this research the availability of data and their spatial analysis led to propose a new lithostratigraphic division within the urban: five units instead of the three suggested by Gutiérrez Claverol and Torres Alonso (1995). This setting was based on several criteria: dominant lithologies, geotechnical properties, stratigraphic superposition and mapping. Additionally, the distribution of evaporitic rocks was better known, reinforcing the mapping of karst phenomena responsible for constructive problems.

## Engineering geology map

The production of an engineering geology map was not a specific objective of the research, as it emerged after obtaining the results already presented. The interpretation of the data and information led to a new surface model for the city, according to the methodology of Díaz-Díaz et al. (2017), but with more data and information and at larger scale (1:15,000). The preparation required updating the geological map; processing the geotechnical parameters; evaluating the experience gained with different subsurface exploration methods; and integrating the geotechnical and hydrogeological behaviour of the ground observed during fieldwork. The establishment of geotechnical zones was based mainly on the dominant materials and their geotechnical properties. For this, three basic types of materials were considered: rock, soil (uniaxial compressive strength below 1 MPa), and mixed rock-soil. Twelve geotechnical units were then differentiated and mapped in the urban subsurface (Table 3). In turn, they were divided into non-mappable subunits formed by competent/weak rocks, and coarse/fine soils. In addition, areas likely to contain hazardous or difficult engineering conditions were mapped: (i) karstified areas; (ii) high

sulfate content; (iii) very plastic soils; (iv) high organic matter content.

The ground behaviour related to building sites was studied by theoretical modelling using the compiled geotechnical parameters. By slope stability analysis based on limit equilibrium methods, feasible inclinations for different heights of slope in open excavations were proposed. For shallow foundations, the bearing capacity was evaluated using analytical and empirical methods. Soil properties with significant influence on foundations such as compressibility, swelling due to water content increase and collapsibility were taken into account. To validate predictions with real experiences, more than 150 construction sites were visited during excavation or at the stage of setting the foundation works. In addition, the most common building damage related to excavations and foundations in the city (e.g. wall cracks) were reviewed to analyse their origin and the construction actions taken. They were mainly caused by slope failures in excavations; unsuitable geotechnical design of retaining walls; loss of lateral confinement of nearby foundations; and settlements due to groundwater extraction. Field monitoring, mainly involving topographical methods, inclinometers, extensometers and piezometers, provided valuable information on the ground behaviour. Various recommendations on the most suitable methods to be used during geotechnical investigations completed the geo-engineering map.

### 3D model

The geological model corresponding to an area of 3 km<sup>2</sup> (Fernández-Álvarez and Pando 2019) was also incorporated. The aboveground three-dimensional representation of roads, buildings (with differentiation of uses), green areas and other urban elements is shown in Fig. 8. The underground space includes basements, underground parking lots and railway tunnels. This recreation provides guidelines on the geometry of the units up to a maximum depth of 168 m, and it is prepared as a starting point for future models based on volumetric units. However, and despite its relative simplicity, the integration of the subsurface environment and the anthropic infrastructure already provides a visually effective model, which offers great versatility for the interpretation and dissemination of results and to inform planning of future structures.

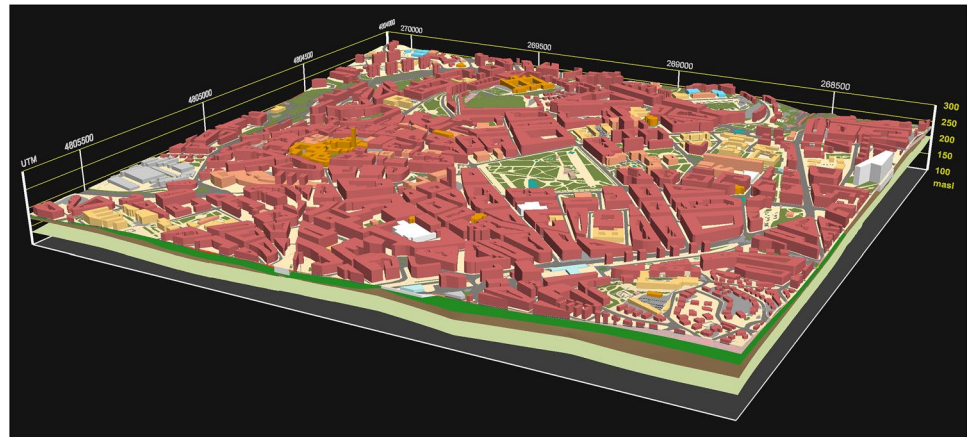
### Conclusions

The aim of building a relational database as the core of the geotechnical system was achieved, allowing the retrieval of an unprecedented amount of ground data in the city. Data analysis using GIS-based functionalities addressed the investigation of specific underground features in Oviedo, providing a better understanding of the bedrock and superficial geology.

**Table 3** Zones and units differentiated in the geotechnical map

Zone	Subzone	Unit	Subunit	Geological unit	Age
(I) Rocks	(I <sub>1</sub> ) Medium strong rocks	I <sub>11</sub>	–	Oviedo Fm	Cretaceous
	(I <sub>2</sub> ) Alternation: medium strong rocks, weak and very weak rocks	I <sub>21</sub>	–	San Lázaro Fm.	
		I <sub>22</sub>	–	Marly-calcareous section	
	(I <sub>3</sub> ) Weak and very weak rocks	I <sub>31</sub>	–	Transitional rudite	
(II) Mixture	(II <sub>1</sub> ) Alternation: weak and very weak rocks, very hard and hard soils	II <sub>11</sub>	Rock Soils	Basal section	Paleogene
		II <sub>12</sub>	Rock Soils	Marly section	
(III) Soils	(III <sub>1</sub> ) Very hard and hard soils	III <sub>11</sub>	Granular Cohesive	Upper section	Cretaceous
		III <sub>12</sub>	Granular Cohesive	La Argañosa Fm.	
	(III <sub>2</sub> ) Firm and soft soils	III <sub>21</sub>	Granular Cohesive	Fluvial deposits	Quaternary
	(III <sub>3</sub> ) Soft and very soft soils	III <sub>31</sub>	Granular Cohesive	Eluvial deposits	
		III <sub>32</sub>	Granular Cohesive	Colluvial deposits	
	III <sub>33</sub>	–	Man-made ground		

**Fig. 8** 3D layer-based model of the city centre



The study of artificial grounds led to the classification and mapping of man-made fills and excavated areas. Their distribution showed the influence of ancient quarries with great historical significance for the local architectural and monument heritage. The mapping of fluvial deposits was improved, making it easier to distinguish them from soils formed by weathering of the bedrock, whose nature and distribution were also investigated. Concerning the structural setting, the spatial analysis based on borehole data led to the identification of vertical offset of stratigraphic contacts compatible with faulting. Faults previously mapped were validated, but others could not be verified, and previously unknown faults were interpreted. Some of the slip-dip faults seems to be related to the Alpine reactivation of Variscan structures. Also, the general features of the main permeable units in both bedrock and soils were analysed for the first time at urban scale, highlighting the hydrogeological impact of some layers within the fluvial–lacustrine series.

The geotechnical parameters compiled can be used for reference, and the geo-engineering properties are useful to predict ground behaviour during future engineering projects as part of the desk study. The analysis of these properties along with other criteria resulted in the proposal of a new lithostratigraphic division within the Paleogene units. The integration of all subsurface data allowed updating of the superficial geological map and the production of a new engineering geology map for the city that includes the distribution of particularly problematic areas for construction. As an additional resource, a preliminary 3D layer-based model of the urban centre was generated. It integrates the underground environment and the urban infrastructure, providing a valuable visualization tool that can be used by a number of different users.

This case study shows the broad scope of use of a GIS-based geotechnical system in a medium-sized city like Oviedo, obtaining significant contributions on the geological setting. These results, based on an exportable methodology,

can encourage similar research in other cities of comparable size with availability of ground data.

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## Declarations

**Conflict of interest** Not applicable.

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