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ORIGINAL ARTICLE

A case of man-induced ground subsidence and building settlement related to karstified gypsum (Oviedo, NW Spain)

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Abstract This paper presents the research carried out to shed light on a sudden settlement and its consequences that occurred in the city of Oviedo. Ground subsidence in the Ventanielles area led to severe damage and the subsequent demolition of two buildings with 362 flats, resulting in losses of 18 million euros. The investigation allowed the identification of a buried sinkhole, filled with up to 13 m of fluvial sediments, linked to the dissolution of a Paleogene gypsum unit with a maximum thickness of 18 m and containing metre-sized cavities. The triggering process that reactivated the paleosinkhole was found to be the pumping of water from a confined aquifer, related to excavation work during the construction of a nearby underground parking lot; this extraction modified the natural hydrological regime. The compaction and migration of alluvial sand towards the karstic cavities were the main subsidence mechanisms responsible for the structural damage, aggravated by the poor quality of the buildings and the geotechnical behaviour of the supporting ground.

Keywords Aquifer · Settlement · Paleogene · Karst · Subsidence · Gypsum

Introduction

Gypsum has a high solubility (2.4 g/l in water at 20 °C) with a dissolution rate that can be up to 100 times greater than of carbonate rocks (Martínez et al. 1998). This characteristic means that, even on a human time scale, the coexistence of evaporitic levels and underground water rapidly leads to the formation of cavities and sinkholes that may present different typologies (Klimchouk 1996; Cooper 1998; Waltham et al. 2005). Gypsum dissolution may lead to a series of related risks, the most frequent of which are the collapse of cavities, ground settlement due to progressive subsidence phenomena, and the aggressive action of sulphates on building concrete. The effects of these processes may be accelerated by anthropogenic activities, particularly enhanced water input into the ground and consequent dissolution process (Cooper 1988; Rodríguez-Estrella and Pulido-Bosch 2010), or a water table decline by pumping works (Lamoreaux and Newton 1986; García-Moreno and Mateos 2011). These factors frequently stem from a previous lack of knowledge on the local geology, and may result in considerable economic losses. The difficulties in identifying zones susceptible to these phenomena are greater in built-up areas; the absence of outcrops and geomorphological evidence (without topographic expression) masks the gypsiferous karst, making the preparation of hazard maps essential when planning the use of land (Paukštys et al. 1999; Richardson 2003). This task has been made easier in recent years thanks to mapping methodologies using different spatial analysis procedures and GIS tools (Kaufmann and Quinif 2002; Yilmaz 2007, 2010; Thierry et al. 2009; Galve et al. 2009, 2011).

Subsidence risks associated with evaporitic sediments are encountered in different countries around the world. Notable in Europe in this respect are, among others, England (Cooper 2002), France (Toulemont 1984), Germany (Reuter and Stoyan 1993; Garleff et al. 1997), Italy (Parise and Trocino 2005; Iovine et al. 2010; Vigna et al. 2010; Fidelibus et al. 2011), Lithuania (Paukštys and Narbutas 1996), Ukraine (Andrejchouk and Klimchouk 1993), and Turkey (Karacan and Yilmaz 1997; Yilmaz 2012). In

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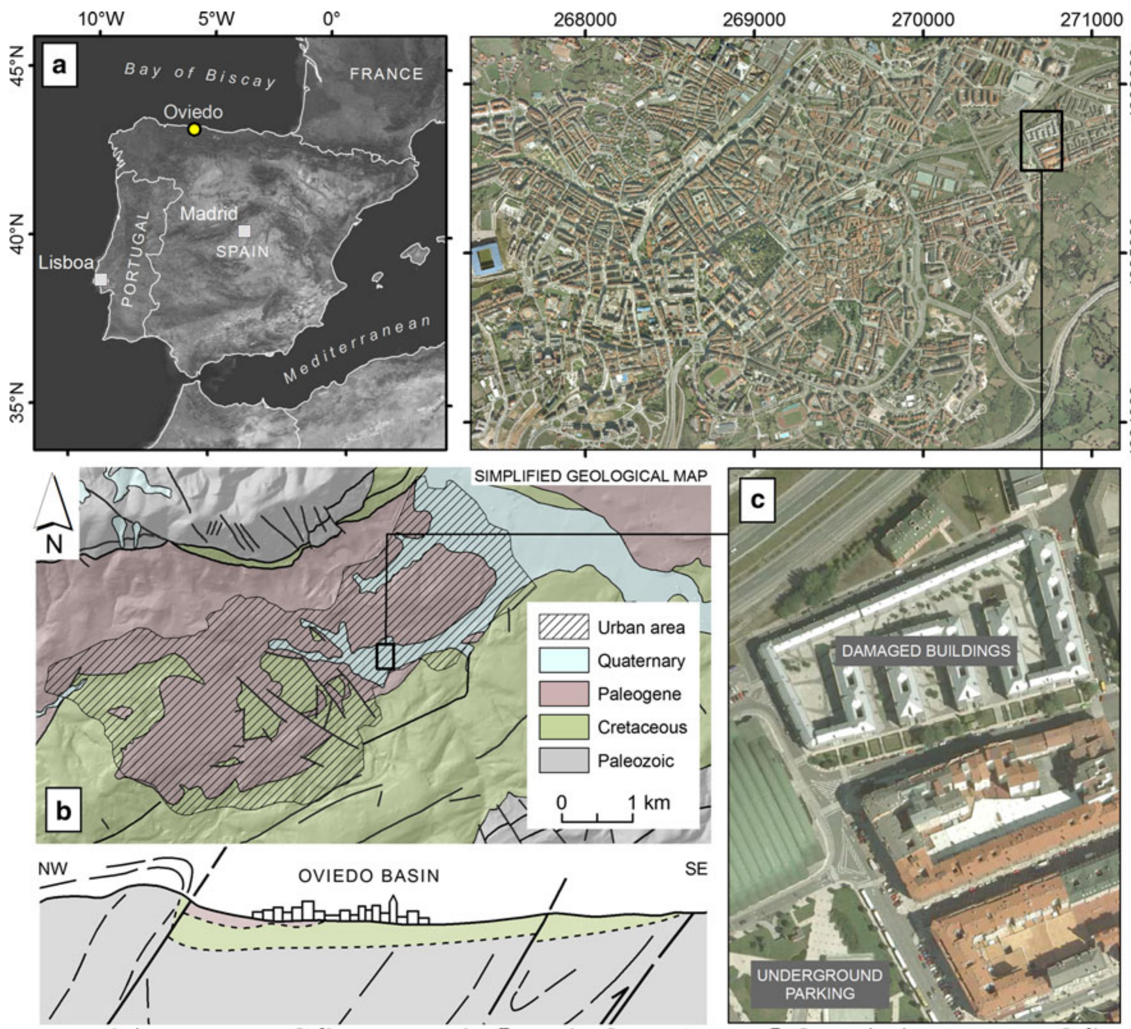

Fig. 1 **a** Location of the studied area; **b** regional geology of Oviedo; **c** Ventanielles neighbourhood

Spain, the karstification of soluble rocks constitutes the main process leading to subsidence problems, particularly in evaporite rocks. The dissolution of Tertiary evaporite formations and the related subsidence phenomena have had a greater socioeconomic impact in recent times, mainly in mantled or alluvial karst settings (Sweeting 1972; Ford and Williams 1989). The most outstanding case is that of the city of Zaragoza (NE Spain) and its environs, with a notable incidence of active sinkholes below communication routes (Soriano and Simón 1995; Simón and Soriano 2002; Guerrero et al. 2004). Nearby examples are those of the town of Calatayud (Gutiérrez 1996; Gutiérrez and Cooper 2002) or the village of Puilatos (Benito et al. 1995), where buildings and roads have been badly affected. Other places in Spain where evaporite rocks are present, though with less profound effects, are in Málaga, Valencia, Gerona, Almería, and Madrid (Gutiérrez et al. 2008).

In the Principality of Asturias, in the NW of the Iberian Peninsula, gypsum of economic interest is found in Triassic and Jurassic formations (González-Fernández et al. 2010), but of particular relevance in terms of their geotechnical incidence are the Paleogene deposits lying beneath Oviedo (Fig. 1a). The presence of evaporite rocks in the city has been known since the 15th century, but their true extent was not evaluated until a few years ago as they lay concealed beneath the urban area. Their considerable thickness and the high degree of karstification became evident as a result of events that occurred in the Ventanielles neighbourhood in 1998. During the construction of an underground car park, a settlement occurred that led to the permanent damage and subsequent demolition of 362 flats, whose replacement had a cost of 18 million euros (Pulgar et al. 1999; Gutiérrez-Claverol et al. 2004; González-Nicieza et al. 2008).

This paper analyses the important social and economic implications of all the available data, starting from the extensive work carried out during the research that took place. The sequence of work followed comprises the description of the local geological and hydrogeological setting and its relationship with the subsidence, the identification of the causal mechanisms and the processes that triggered them, and finally an assessment of their contribution to the ground settlement.

Background

Oviedo (population 215,000) is located in a Mesozoic–Paleogene basin with a gentle ENE–WSW oriented synclinal structure, affected by major steeply dipping reverse faults and minor steeply dipping subvertical faults, and situated on a basement of strongly folded Devonian and Carboniferous formations (Fig. 1b). The Cretaceous series consists of alternating carbonate and siliciclastic rocks, with two units chiefly outcropping in the city area: La Argañosa Formation and Oviedo Formation. The former consists of a succession 40-m thick of highly permeable sands that forms a regional aquifer. It is overlain by the Oviedo Formation, which is made up of approximately 15 m of greyish-orange sandy limestone that forms a palaeorelief. The unconformable Paleogene series is fluvial and lacustrine in nature and is mainly composed of marls and clays, with intercalated calcareous and gypsiferous layers. The proportion of carbonate sediments decreases towards the top but in places reaches a thickness of 200 m (Gutiérrez-Claverol and Torres Alonso 1995). With regard to the geomorphic features there are limited data. Fluvial processes and the weathering of calcareous rocks are the most relevant phenomena, but the human activities (earth-moving works) have modified notably the natural landform of the built-up area; all the streams were eliminated, and the alluvial deposits and residual soils lay now concealed below man-made fills. Also, the forms of surface karst are not recognisable.

The Ventanielles area is located in the eastern and topographically lowest part of the city. At the beginning of the 20th century, the urban planning had earmarked this zone for industrial use, but given its clayey subsoil with poor natural drainage, the ground was often flooded. To mitigate this problem, waste material was dumped and the streams running through it were channelled towards collectors. However, during the years of economic hardship in the middle of the last century, a decision was taken to build a number of blocks of flats for socially disadvantaged classes. The buildings were constructed between 1955 and 1965. Due to the substandard state of the materials used, among other factors, within a short time the buildings began to be affected by faint cracks in the façades and by aluminosis. At the same time, the presence of underground water near the surface caused frequent flooding in the flats that were partially below the street level.

During the month of July 1998, excavation works for the construction of a three-storey underground parking lot were carried out in the proximity of the affected buildings (Fig. 1c). Continuous slopes with a gradient of 1H:1V were excavated. When a depth of 3 m was reached, water began to flow in from a shallow aquifer, which was pumped out without any difficulty. After the maximum planned depth of 9 m was reached, digging continued 2 m further down on one side of the site for the foundation of a crane (Fig. 2). As a result, the top of a gypsum unit was reached and a considerable amount of water flowed in. The volume of water proved to be far greater than before, so much so that it brought the work to a standstill and, although this water was initially pumped out, the amount of inflow became equivalent to the outflow and the site was flooded.

In conjunction with this, at the beginning of August, the occupants of several buildings reported the occurrence of cracks inside their flats as well as the reactivation of other earlier cracks in the façades. In particular, badly affected was block No. 8, located 100 m away from the parking lot (Fig. 1c). The damage extended to nearby buildings and to the pavements and road surfaces of several streets. Due to the severity of the damage and the threat of collapse, the municipal authorities dictated the evacuation of the worst affected buildings in the middle of August, only 10 days after the first cracks formed, and immediately these buildings received extra structural support. At the end of the month, when the pumping operations at the site ceased, the cracks stopped growing in size.

Finally, in September, the technical team in charge of the parking lot construction work filled the bottom of the excavated cavity with blocks of limestone, resulting in the loss of a storey with respect to the initial plan. After this measure had been taken, pumping operations were resumed and sealing and containment measures applied by means of a raft foundation and a retaining wall. It has been calculated that more than 17,000 m^3 of water was pumped out during this period. The Asturian Government assumed the task of demolishing the buildings, resettling the occupants, and financing the rebuilding work. Overall 362 flats were affected by this measure. The new blocks of flats, designed with deep foundations like the rest of the buildings in the vicinity, were completed and the affected families returned there in 2002.

Methods

After the damage appeared, a photographic inventory and maps of the affected area were produced. Monitoring was carried out by installing plaster patches and measuring devices (displacement), to gain data on the movements of the cracks. At the same time, tacheometry was performed

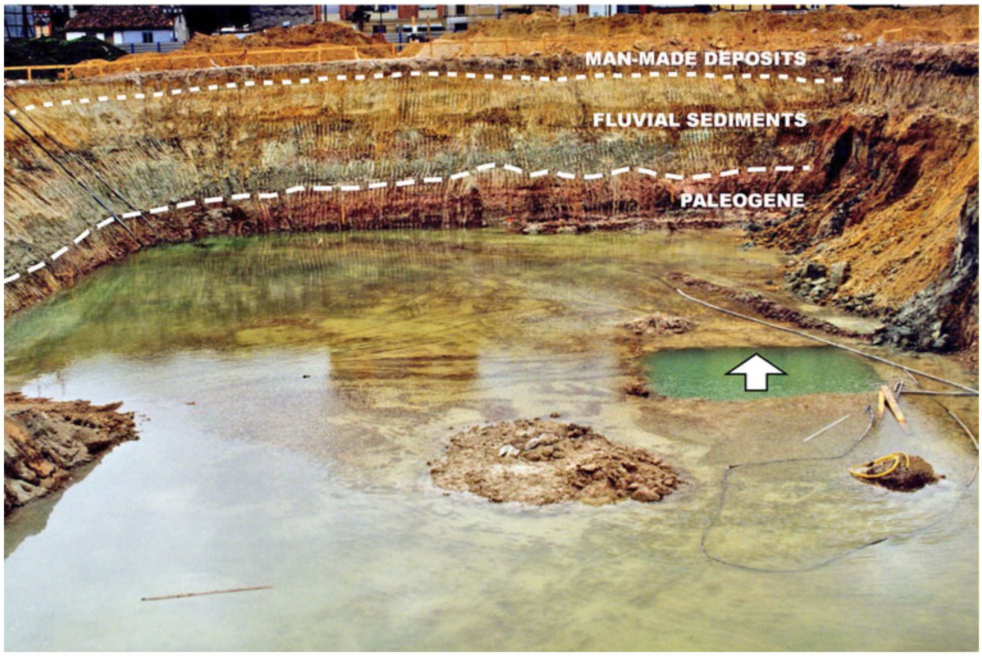

Fig. 2 Parking lot construction with deeper rectangular hollow for a crane foundation through which groundwater raised and flooded the excavation

to determine the spatial distribution of the settlement. To identify the mechanisms involved in the subsidence process, the geological configuration of the area and the properties of the materials were investigated. The corresponding field campaigns, extended in later studies, started when construction of the parking lot was still in progress and continued until the end of 1998. During the investigation the following techniques were used:

- *Boreholes* Data were compiled from previous prospection works; this included 11 boreholes prior to the construction of the buildings (1954). After the event of 1998, 34 additional boreholes were drilled, with lengths between 10 and 50 m. Overall, they provided more than 700 m of logs, covering a surface area of 28,000 m^2 (Fig. 3).
- *Geophysical surveys* Initially, ground penetrating radar was used to detect underground voids, using antenna frequencies of 200 and 80 MHz; 12 profiles were realised (more than 1,500 m of linear survey). Later, the investigation was supplemented with borehole techniques (seismic and GPR tomography) to recognise in detail the karstified zones. Also, the morphology of the bedrock was studied using refraction seismic (4 profiles, total length of 500 m).
- In situ geotechnical tests (standard penetration test and pressure meter) performed at different depths.

For the hydrogeological characterisation, piezometers were installed in most of the boreholes and water levels were checked on a daily basis during the first 3 weeks. Lefranc permeability tests were also performed. Altered and unaltered soil and rock samples were taken from the cores for laboratory testing to determine their classification, "index properties" and mechanical behaviour. The water samples were chemically analysed for contents of free chlorine, chlorides, sulphates, carbonates, sodium, oxidability, faecal and total coliforms.

Results

Building damage and subsidence

The measurements of cumulative settlement in the affected area define a closed depression (Fig. 4a), with maximum subsidence of 60 cm, and a differential settlement of the western portion of the blocks over 30 cm. It is worth pointing out that these measurements correspond to the total subsidence suffered by the buildings since their construction was finished in the 1960s. The increase in settlement produced exclusively by the events of 1998 is unknown due to the lack of previous studies. In any case, in these conditions the angular distortions proved to be unacceptable for the buildings ($\delta > 1/150$), causing the cracks to increase in size at an extraordinary quickness (Fig. 4b, c); the widening rate measured was up to 2 mm/day. To interpret the cracks it was necessary to know the relative movements suffered by the blocks of flats, and the

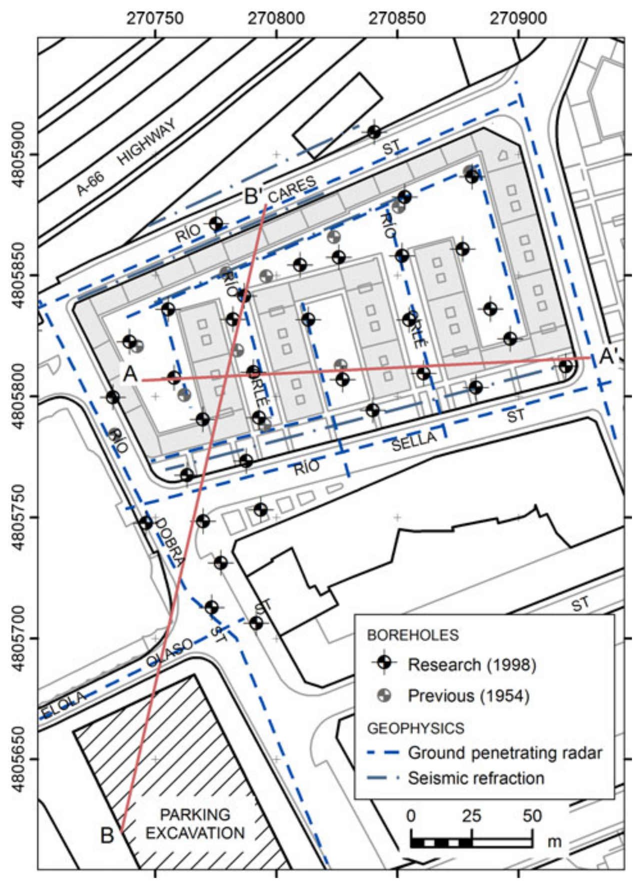

Fig. 3 Distribution of the boreholes and geophysical surveys used to study the area affected by settlements

differential settlement with the greatest subsidence occurred in the western sector of the central building. This tendency was confirmed in its NW eaves, where a horizontal displacement of 20 cm towards the west was measured.

Geological setting

The boreholes provided valuable information about the subsoil and allowed us to infer the stratigraphic log for this part of the neighbourhood. The stratigraphic sequence is quite similar to the rest of the city, but with a remarkable thickness of the Quaternary sediments and a higher amount of gypsum than any other area in Oviedo. GPR profiles permitted identification of buried installations and services, ensuring drilling could be carried out safely. Although GPR surveys were carried out with antennas of different frequencies, they highlighted a few anomalies linked to geological features. The inefficiency of the method seems to have been due to underground water and its extremely sulphate-rich nature, which favoured the deviation of the electromagnetic radiation, as well as to the abundance of clayey sediments, which absorbed the GPR signal and limited the investigation depth. The data obtained using seismic technology in boreholes and GPR tomography proved useful in determining the distribution of the karstified zones, aiding in the detection of cavities. With the help of the research carried out, it was possible to define the following stratigraphic units:

- *Man-made fill* Accumulation by uncontrolled dumping of poorly compacted heterogeneous remains from demolition and excavation work, with marked variations in thickness. The average thickness lies between 1 and 2 m, with maximum values of around 5 m.
- *Quaternary alluvial deposits* Resulting from the confluence of several ancient streams, the thickness varies between 4 and 13 m (Fig. 5a, b). From top to bottom, they consist of the following units:
  - *Organic-rich sediments* Dark organic clays and high-plasticity silts with a maximum thickness of 6 m. The composition has been strongly conditioned by human activities, especially related to contamination due to sewage and industrial waste from a nearby slaughterhouse.
  - *Clays* Comprising ochre and greenish silty clay and sandy clay deposits up to 9 m thick.
  - *Sands and gravels* Yellowish and greyish silty sands with rounded siliceous pebbles. The maximum thickness is on the order of 6 m.
- *Paleogene* Detrital-carbonate and evaporite sediments over 30 m thick. Different units have been identified:
  - *Marly clays* Reddish and green marls and clays up to 13 m thick with variable carbonate content.
  - *Gypsum rock* Massive gypsum rock unit with dark-coloured calcareous lenses whose composition was confirmed by X-ray diffractometry. Its thickness reaches 18 m in the southern section and it is highly karstified, with cavities up to 4.5 m in height (Fig. 5b).
  - *Clayey marls* Similar to the marly clay unit, though marls predominating in the lower part.
  - *Calcareous sandstones* Fined-grained, pinkish-brown and green cemented sandstones with disperse calcareous pebbles. Up to 6-m thick, it has a gradational basal contact.
  - *Conglomerate* Poorly sorted Cretaceous limestone pebbles with a matrix of reddish-brown sandy marl or sandy clay material, partially cemented. Although it has a gradational top contact and its thickness is very variable, a maximum value of 14 m has been recorded.
- *Cretaceous* Greyish-orange limestone of the Oviedo Formation, with abundant sand-sized detrital particles

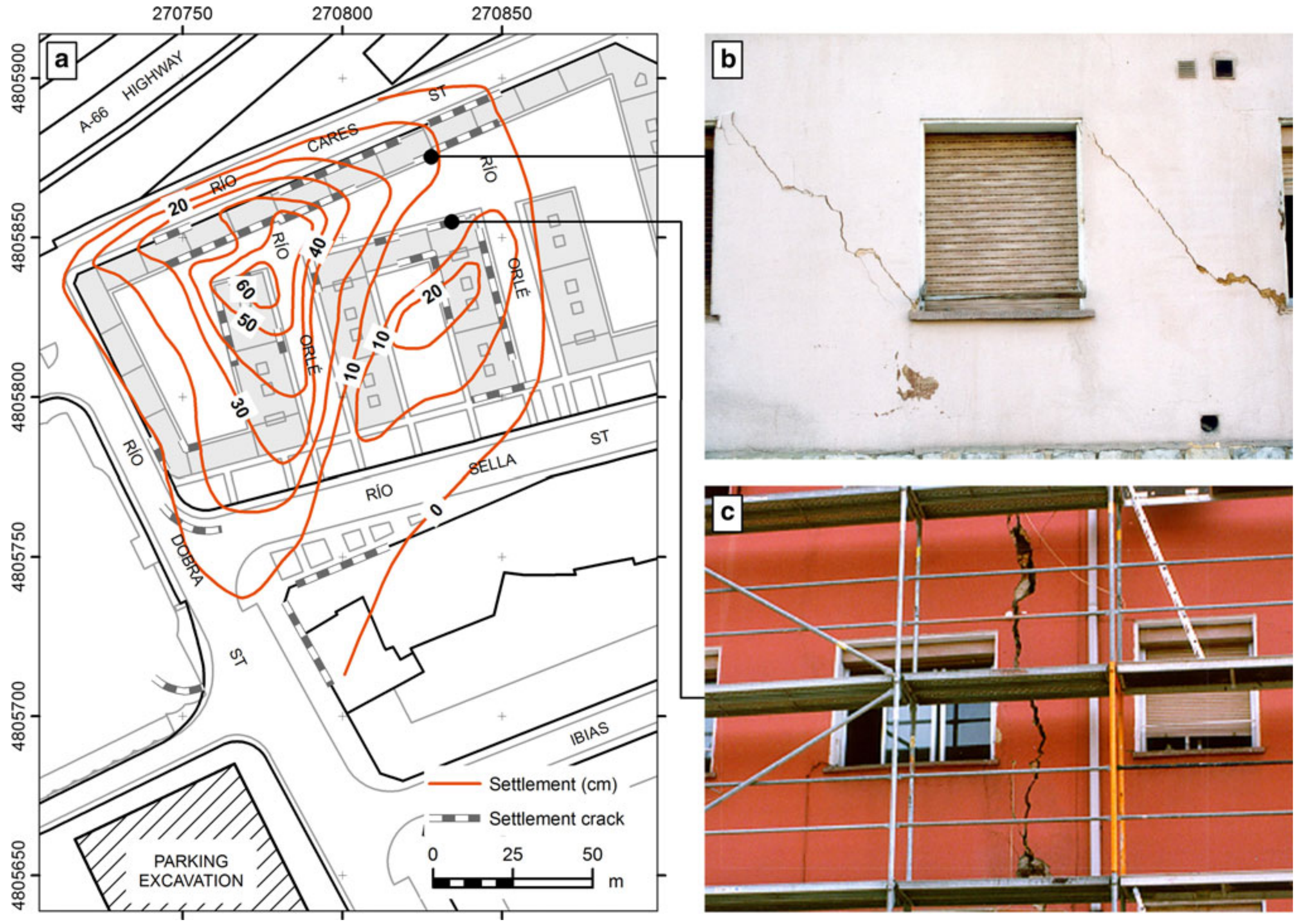

Fig. 4 **a** Isolines of total settlement and distribution of the damage suffered in the façades of the buildings and road pavement surfaces; **b** cracks with an inclination of 45° caused by differential subsidence; **c** vertical crack on a façade, with the greatest gap in the upper part (>10 cm) due to the partial tilting of the building

and signs of karstification. It was not possible to estimate its total thickness as its base was not reached.

With regard to the geological structure, the Quaternary sediments define a fill with an inverted cone shape, while the Paleogene strata show a subhorizontal attitude a down to the east, with NNE–SSW trending faults (Fig. 6).

Geotechnical properties

The results of the laboratory tests illustrate the low geotechnical quality of the Quaternary materials (Table 1). The uppermost alluvial sediment is dominated by organic clays (OH) and high-plasticity silts (MH). These have a low specific weight and extremely variable content in organic matter (averaging around 9 % with maxima to 18 %). Samples exceeding 30 % had been recorded in this area in previous studies. The underlying unit corresponds predominantly to low-plasticity clays (CL) with some high-plasticity components (CH) and an average organic material content that reaches 4 %. The bottom unit of the alluvial deposit is chiefly made up of sands with gravels (SP) and some pebbles along with silty sands (SM). Fluvial sediments exhibit very low average mechanical strength when subjected to uniaxial compression (<0.1 MPa), particularly in the high-plasticity soils. The values increase in the Paleogene clays and marly clays, 0.26 and 0.10 MPa for groups CL and CH, respectively; thus, its mechanical behaviour improves on with regard to the fine-grained alluvial sediments. The UU type direct shear tests performed on clays and silts have provided low friction angles in the Quaternary sediments in the low-plasticity clays, which are the most frequent in the local subsoil. These are always below 17° with an average undrained cohesion of 48.02 kPa and a noticeable dispersion of values. In the oedometric tests, the high index of compression corresponding to fine organic material reveals its marked tendency to induce excessive consolidations when supporting the weight of foundations.

The lower units have greater mechanical behaviour. The compressive strengths of the massive gypsum range

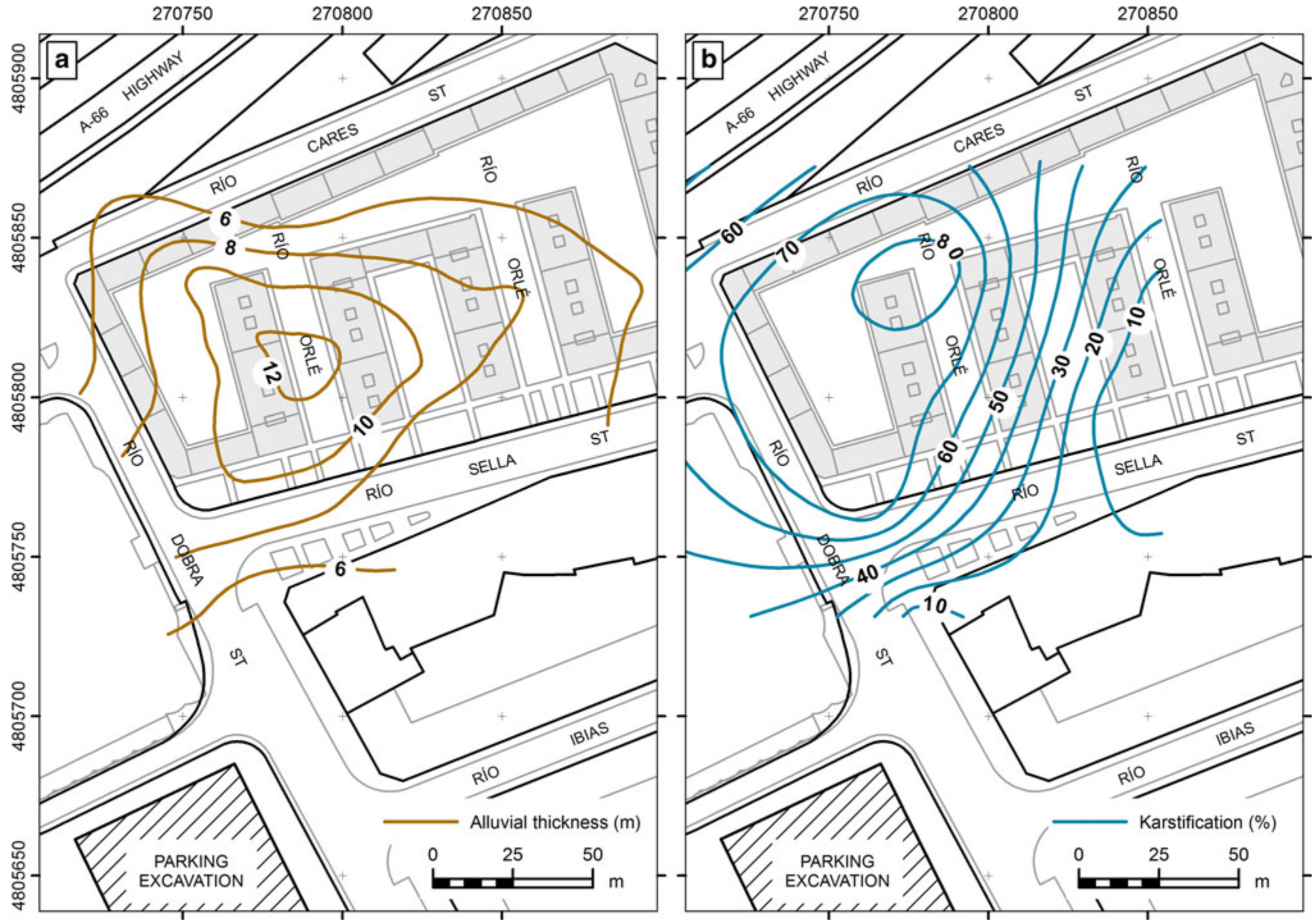

Fig. 5 **a** Isopachs corresponding to the fluvial deposits; **b** dissolution of the gypsiferous sequence estimated from rock quality in borehole cores

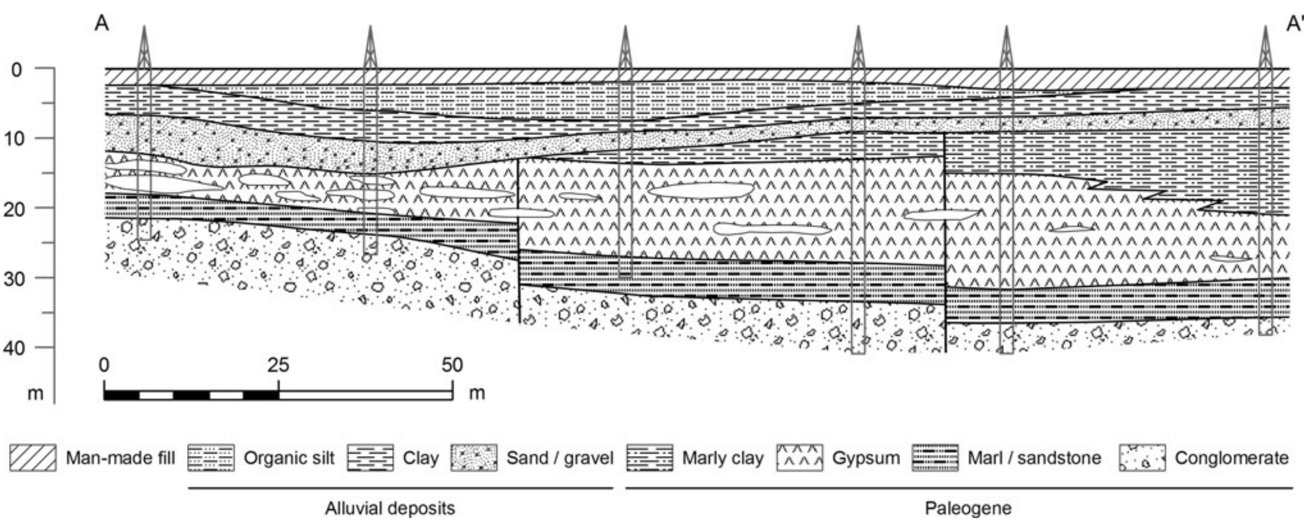

Fig. 6 Geological section (A–A′) constructed by means of boreholes (see Fig. 3)

between 9.22 and 36.47 MPa. The values are lower for the calcareous sandstones, 18.04 MPa in average, and are largely dependent on the carbonate content. In the basal conglomerate, given the heterogeneity that results from the varying proportion of pebbles and matrix, the average value measured falls to 7.49 MPa. Finally, the Cretaceous

Table 1 Summary of geotechnical parameters obtained in the laboratory tests

	USCS	w (%)	γ (kN/m^3)	w_L	w_P	I_P	OM (%)	σ_c (MPa)	$\varnothing_u$ (°)	c_u (kPa)	Cc
Quaternary											
Fine-grained alluvial	OH		13.82	57	35	22	9.7	0.02	4.63	23.52	0.378
	MH		18.52	57	33	24	9.3	0.04	13.65	52.43	
	CL	25.3	18.72	39	18	21	4	0.07	12.81	48.02	
	CH	57.7	17.93	68	33	35	1.9	0.03	7.8	29.40	0.19
Coarse-grained alluvial	SP–SM	34.9	19.31	35	22	13		0.06			
Paleogene											
Clay and marly clay	CL	25.6	19.8	40	19	21		0.26	26.78	74.73	0.108
	CH	41.4	17.93	64	33	31		0.10			
Gypsum								25			
Sandstone								18.04			
Conglomerate								7.49			
Cret.											
Limestone								39.09			

w natural moisture content, γ apparent specific gravity, w_L liquid limit, w_P plastic limit, I_P plasticity index, *OM* organic matter content, σ_c uniaxial compressive strength, $\varnothing_u$ undrained friction angle, c_u undrained cohesion, *Cc* compression index

limestone has the highest mechanical strength values, up to 56.86 MPa.

This information was used to determine the theoretical load-bearing capacity of the sediments underlying foundation of the damaged buildings; strip footings transferring between 100 and 200 kPa to fluvial silts and clays. Using the analytical polynomial formula proposed by Hansen (1970), the ultimate bearing capacity that was calculated falls below 300 kPa. This is a very low value, close to the contact pressure exerted by the buildings, indicating unacceptable critical safety conditions for direct foundations according to the present-day standards.

Hydrogeology

Hydrological characterisation proved to be difficult, since it was such a complex matter to identify piezometric levels in these lithologies; the Quaternary sediments show very different hydraulic conductivities and the Paleogene deposits have marked lateral changes in facies. In addition, it was known that pumping tests in karstified areas are difficult to apply (Crochet and Marsaud 1997). Finally, based on the piezometric levels identified, three stacked aquifers were recognised:

- *Superficial aquifer* It owes its existence to the porous man-made fills. It is sealed at depth by the fine alluvial material, the permeability of which was calculated to be 10^{-7} m/s using Lefranc tests. Its hydrological behaviour is conditioned by a residual water collector that runs through the area, resulting in an alternating exchange of water (recharges the deposit during the rainy periods and drains it during the dry periods).
- *Alluvial aquifer* Situated in the fluvial gravels and sands and corresponding to an underground watercourse, the estimated hydraulic conductivity ranges between 2.6×10^{-1} and 1.6×10^{-2} m/s. The underlying marly clay aquitard ($k = 10^{-7}$ m/s) acts as a low-permeability bedrock.
- *Karstic aquifer* Located in the Paleogene gypsum, it is a confined aquifer since it is overlain by the aquitard clays. Its artesian behaviour was verified during the excavation works for the underground parking lot.

In the investigated area the sands and gravels rest directly on gypsum deposits (Fig. 6), a configuration that was not detected by González-Nicieza et al. (2008), and chemical analyses indicated contamination due to sulphates in samples of water taken in the fluvial sediments. Under these conditions, the two aquifers are connected and a change in the piezometric level adversely affects the behaviour of both. From the end of August, the piezometric evolution of this aquifer system was monitored, and this enabled us to confirm that while water was flowing out of the bottom of the excavated area, an underground water flow was established with a NNE–SSW orientation towards the excavation (Fig. 7). This caused the piezometric level to fall by at least 2 m. This flowpath is very different from the natural flow trend in this part of the town (WSW–ENE). The water level does not fall below the top of the gypsum unit, but causes the detrital cover to act as a drain towards which the alluvial flow lines converge, a circumstance which is favoured by its morphology of an inverted cone.

Another indication of a connection between the karstic and alluvial aquifers is that during the drainage work in the excavated area, there was a decrease in the volumes of

Fig. 7 Depth of the water table causing groundwater flow oriented towards the excavated area during pumping

water evacuated from the garages of other nearby buildings equipped with pumps. This situation continued until the pumping finally stopped, the piezometry stabilising in mid-September, 1998. At the same time, the rate at which the monitored cracks were widening slowed down progressively.

Discussion

Natural ground subsidence

The subsoil under the buildings that suffered the greatest damage is defined by a depression of the gypsum bedrock, which appears karstified and covered with fluvial deposits. The deep inflow that feeds the karstic system appears to come from a regional Cretaceous aquifer, which corresponds to the sands of the La Argañosa Formation and in this part of the town has a flow in SW–NE direction. It reaches the gypsum by rising through fractures cutting the Mesozoic–Paleogene succession, a hypothesis supported by the significant degree of karstification observed in the Cretaceous limestone during the examination of rock cores obtained from boreholes. This underground flow, sealed at the top by low-permeability Paleogene sediments, has enabled the formation of karstic conducts. During the hydrogeological evolution of the basin, the piezometric level must have undergone variations that amplified this effect until virtually the entire gypsum unit was affected.

Probably the streams eroded the top of the Paleogene sequence formed by marly clays, uncovering the gypsum unit which lies here shallower than in other areas. The karstic and alluvial aquifers were connected, and the capture of surface drainage improved the karstification of the bedrock even more. This area evolved then by the combination of inter-related processes, mainly the gypsum dissolution below saturated soils, with also small-scale collapse and particles down-washing into voids (fissures and cavities) in the underlying bedrock. These phenomena caused a local slow subsidence and gradual thickening of the detrital cover sediments whose settle progressively. Furthermore, no relationship was found between the sinkhole development and the organic-rich deposit as it has been established in other cases (Margiotta et al. 2012). Finally, attending to the morphologic features, the main formation process and the engineering hazard, this setting can be interpreted as a buried sinkhole (Waltham et al. 2005).

The term "buried" does not mean necessarily that dissolution is inactive. Effectively the local conditions confirm that nowadays karstification is active in the area. These conditions have been seen elsewhere (Johnson 1996; Martínez et al. 1998; Lamont-Black et al. 2002) and include the presence of evaporite rocks, water with the capacity to dissolve them, energy for the water to flow through the system, and an outflow point. The natural content of sulphates in the aquifer that feeds the underground flow system is close to 20 mg/l in Oviedo, but in the Ventanielles area concentrations in excess of 1 g/l have frequently been measured. Moreover, these anomalies extend in NE direction, in an area not interested by the presence of gypsum.

Induced subsidence

Natural subsidence phenomena are present on the site. However, the rapid increase in damage occurred at the same time as the underground drainage during the parking lot excavation work. This circumstance points to the human-induced deviation of the groundwater flow as the main triggering process in the sudden acceleration of the settlement and the consequent failure of foundations. In such a geological context, the fall in the piezometric level can give rise to different subsidence processes. The potential contribution of each one has been evaluated separately. A geological section representative of the area of maximum settlement has been used for this purpose, and

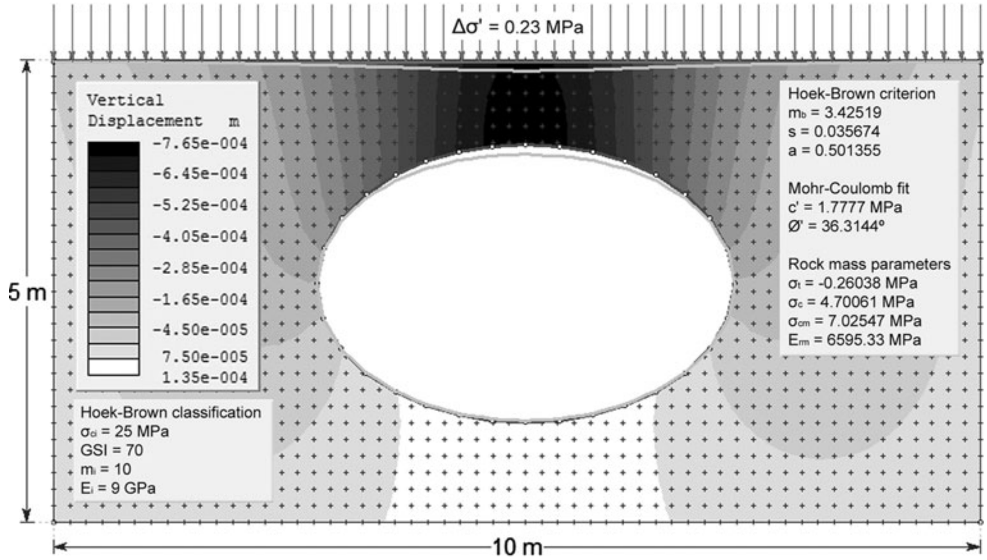

Fig. 8 Modeling a cavity within the gypsum bedrock and deformed by the effective stress increase

the effects of a piezometric fall have been analysed in two situations: for water level decline of 2 m, as occurred during a large part of the pumping work, and lowering of 8 m, an extreme hypothetical situation equivalent to a drop to the base of the granular alluvial section. The factors we analysed were as follows:

- *Increase in the dissolution rate* The dissolving action of water is favoured, among other factors, by an increase in the hydraulic gradient and the flow velocity in karstic channels. Both effects occur in this case, the gradient induced during the pumping operations is at least one order of magnitude higher than the gradients normally measured in this area. However, this mechanism, more characteristic of granular strata than of fissures, does not act with sufficient rapidity to explain the immediate effect observed in the study case.
- *Collapse of cavities in the gypsum* The decrease in hydrostatic support at the top of the cavities may cause the roof material to deform and to collapse under the loads exerted by the foundations and the weight of the overburden. In this case, we can also state that the maximum settlement corresponds to the area having the greatest degree of karstification. To study the effect of the fall in water level on the tensional and deformational state of a cavity located in gypsum and covered by material of variable thickness (between 0.25 and 1 m), this setting was analysed by numerical simulation, using the Rocscience Examine^{2D} (boundary element method) and Roclab programs. The latter allowed us to obtain the mechanical strength parameters of the rock mass according to the Hoek-Brown criterion (Hoek et al. 2002). The results show that the increment in effective stress is so small with respect to the mechanical quality of the rock that its influence on the safety factor is minimal. In terms of elastic deformation there is an increase of around 30–50 % with respect to the initial conditions, though these values are very low. In the hypothetical case of the most critical load and a cavity roof of only 25 cm, it still decreases by less than 4 mm and does not exceed 1 mm for a roof 1 m thick (Fig. 8). Really it is found that no cavity becomes unstable with the water table of the alluvial aquifer decreasing completely during the pumping work. Thus, this mechanism is concluded to be of quantitatively negligible incidence, assuming that the mechanical parameters of this karstified rock mass show uncertainty, and considering as well that gypsum has creep behaviour.

Related to this, experience shows that no problems were encountered in other buildings with deep foundations supported by the karstified level (e.g. Oviedo Sports Palace), confirming that the collapses of the bedrock are not active phenomena here. We cannot actually rule out the possibility that they have occurred on a small scale, but there is no conclusive evidence.

- *Compaction and consolidation of sediments* The dissipation of interstitial pressure through loss of water is a normal phenomenon in detrital sediments saturated under a heavy load. To assess the subsidence associated with the fine fluvial deposits, their settlement due to primary consolidation was calculated based on the oedometric data. For this purpose we considered ground consisting of 2 m of organic silts and 4 m of clays, normally consolidated, subjected to an excess load of 2 m of superimposed fill and the pressure exerted by the foundations. The theoretical settlement thus obtained exceeds 40 cm, meaning that this may be the process responsible for the slow, gradual settlement of the blocks of flats since their construction. With

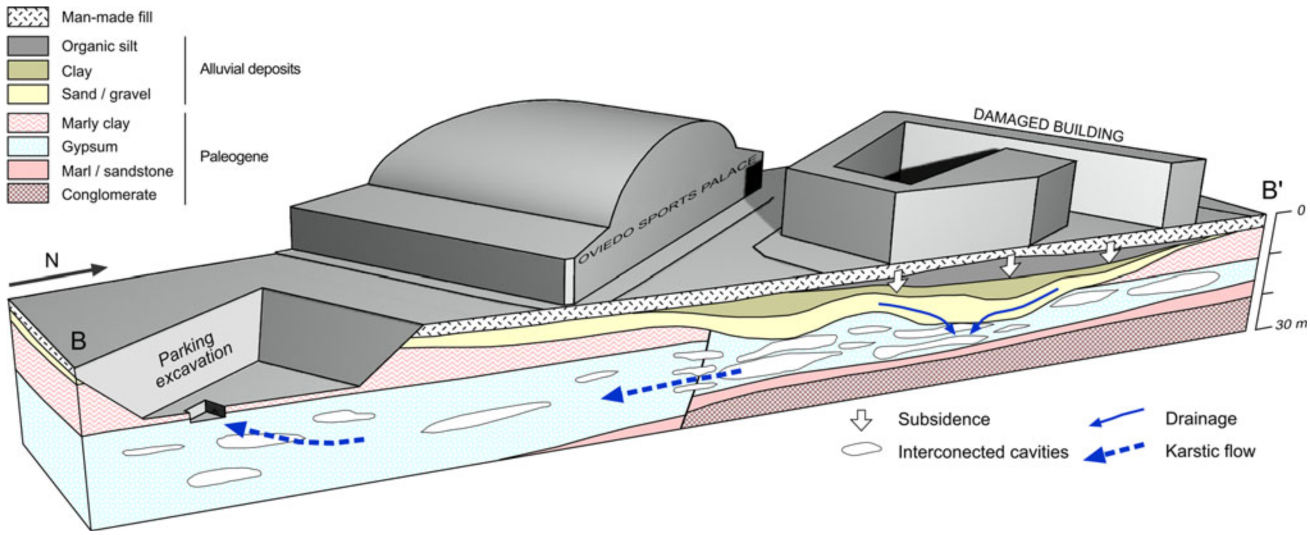

Fig. 9 General 3-D scheme of the occurred subsidence phenomena (see Fig. 3)

regard to the deposit of sands and gravels, the settlement caused by the excess load placed on them by the housing area is instantaneous, but the increase in effective stress resulting from the decrease in the column of water and the corresponding downward flow produce additional compaction during pumping work. The highly porous nature of this section (porosity around 42 %) favours this process, as does the fact that the worst affected area is located over the thickest granular alluvial sediments (6 m). A quantitative approximation to the potential compaction of this deposit indicates that, in conditions of complete depressurisation of the alluvial aquifer, a decrease of just 1 % in the void ratio represents a theoretical settlement of several centimetres.

- *Internal erosion of particles* The underground flow induced by pumping may cause the soil to be transported towards the karstic system if, as is the case here, the detrital cover rests directly over a dense network of pre-existing cavities. Using the average permeability values and the flow maps produced, we were able to estimate infiltration speeds accelerated up to 2 cm/s in the upper part of the sands unit. At the bottom of the fluvial sequence it was not possible to establish a detailed flow network, due to the absence of reliable information about the volumes of water extracted. However, it is thought that the hydrodynamic forces exceed locally the critical hydraulic gradient during drainage. Also, the subsurface erosion processes were probably favoured by the groundwater level oscillations induced by the pumping works and their interruptions (flooding and draining cycles). When the data obtained during the inspection of boreholes were examined, in particular those located in the area with the highest concentration of damage, "piping" evidence attributable to recent internal erosion was observed in the soil cores, and also detrital sediments discharged by the water were found filling several cavities (Fig. 9).

Conclusions

In summer 1998, during excavation works for an underground parking lot, cracks appeared in a group of buildings in Oviedo. This led to the demolition of 362 flats threatened by structural collapse. A maximum settlement of around 60 cm was measured at the surface. The investigation carried out, boreholes, geophysics and laboratory tests, allowed the detection underneath the worst affected area of a paleosinkhole filled with more than 13 m of alluvial sediments over massive Paleogene gypsum with a high degree of karstification and metre-size cavities. Three aquifers were identified; a semiconfined gypsum karst aquifer and two superimposed unconfined ones. Of the latter two, one was in alluvial sediments and the other in man-made fills. The karstic and the alluvial aquifers were connected in the doline.

The investigation of the subsidence phenomenon linked to a piezometric fall and capable of causing such a sudden process enables us to distinguish two stages of man-induced subsidence that have affected the buildings. The first, slow and progressive, acted from the time this neighbourhood was built and is due to the consolidation of fluvial silts and clays with abundant organic matter. It is responsible for the major part of the settlement observed. The second, sudden and immediate in its effects, is related to the pumping operations during the parking lot construction work. This drainage, coincident with the development of the damage, as has been observed, caused a drop in the level of the karstic aquifer, which in turn led to a piezometric fall in the alluvial aquifer; the natural flow network was deviated accordingly towards the excavation, acting the paleodoline as a drain for the water.

During the extraction of water, it was shown that the collapse of cavities was a highly unlikely phenomenon since the increase in effective stress is insufficient in the most unfavourable conditions, which involves a complete fall in the water table of the alluvial aquifer. An increase in the dissolution capacity of the water was also ruled out due to its slow velocity. The available data indicate that the sudden settlement was linked to the fluvial gravels and sands, and was caused by the combined effect of their compaction due to loss of water and the internal erosion of particles towards the karstic cavities, owing to the large size of the latter and the high gradients resulting from the pumping operations. In this particular case, the rapid action of these mechanisms was aggravated by the susceptibility of the buildings to any abrupt change in the state of the foundations due to their poor quality of construction, and the reduced load-bearing capacity of the supporting ground. This accelerated the structural consequences of the gradual settlement.

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