

Instrumental monitoring of the subsidence due to groundwater withdrawal in the city of Murcia (Spain)

Juan Manuel Pardo · Antonio Lozano ·
Gerardo Herrera · Joaquín Mulas ·
Ángel Rodríguez

Received: 28 June 2013 / Accepted: 31 July 2013 / Published online: 15 September 2013
© Springer-Verlag Berlin Heidelberg 2013

Abstract This paper presents the results of investigations of the generalized subsidence occurring in and around the city of Murcia, Spain. Based on this research, this is the first integrated investigation of its type performed in Spain. The phenomenon of ground consolidation in the city of Murcia leads to the appearance of severe cracking and settlement in buildings. Subsidence is the result of two factors: on the one hand, the nature of the ground in this area, as it is made of recent deposits of clay and soft limes filled in with clay–lime backfills in the top layers. On the other hand, the increase in groundwater withdrawal during the 1992–95 drought led to a decrease in the water level of a magnitude never before recorded in the city. The risk prevention management suggested convenience of the installation of a measurement network to study and follow the phenomena of the subsidence to quantify it and to calibrate this theoretical model. This network is composed of extensometers and piezometers, the best devices to measure moderate ground

movements, which is the case of Murcia. The first phase (Phase I) of this study of ground settlement in the metropolitan area of Murcia involved the installation of a network with 22 extensometers and taking the first measurement series. In a second phase (Phase II), during a period of 4 years, measurements with extensometers were performed to make the analysis and calibration of the theoretical model. Experience and data analysis showed the convenience of installation of new control points with an incremental extensometer and a piezometer in close position with the aim of precisely correlating piezometric levels with the observed subsidence. The third phase (Phase III) started in 2007, a new control technique, based on radar interferometry (InSAR), is being employed to provide information about subsidence in areas not previously monitored.

Keywords Murcia · Subsidence · Monitoring · Extensometer · InSAR

J. M. Pardo (✉)
Instituto Geológico y Minero de España,
Matemático Pedrayes 25, 33005 Oviedo, Spain
e-mail: jm.pardo@igme.es

A. Lozano · Á. Rodríguez
In Situ Testing, Avenida de los Pirineos 25-27,
San Sebastián de los Reyes, 28700 Madrid, Spain
e-mail: alozano@insitutest.com

Á. Rodríguez
e-mail: ars@insitutest.com

G. Herrera · J. Mulas
Instituto Geológico y Minero de España,
Ríos Rosas 23, 28003 Madrid, Spain
e-mail: g.herrera@igme.es

J. Mulas
e-mail: j.mulas@igme.es

Land subsidence caused by lowering of the water level

Land subsidence is a phenomenon that implies ground surface settlement. It is because of several factors such as: underground mining and tunnels, morphotectonic processes and sedimentation, consolidation of organic and soft soils, withdrawal of oil and gas, and groundwater withdrawal being the more important ones.

Common features of subsidence by groundwater withdrawal are: the effects are visible over large areas and long periods of time. The quaternary (Holocene) cohesive soils of medium–low compactibility, which originated in alluvial, lacustrine or shallow marine facies, are the most susceptible materials to undergo a process of consolidation over time.

All over the world, groundwater pumping from deep wells has led to decreases in piezometric levels as large as 153 m measured in San Joaquin Valley (California, USA) (Poland et al. 1975) and rates of 5.4 m/year in the area of Houston–Galveston, Texas, USA (Lockwood 1954). Also, settlements of more than 850 cm have been measured in San Joaquin Valley and Mexico City (Poland 1984).

Some movements extend to huge depths, even more than 200 m in San Joaquin Valley, Central Arizona (Jachens and Halzer 1982), Houston–Galveston, USA, Bangkok, Thailand (Piancharoen 1977), Niigata and Tokyo, Japan (Takeuchi et al. 1969). The area involved can be very large; for example, in 1973, a surface of 13,500 km² reached a settlement minimum of 30 cm in San Joaquin Valley.

Terrain lowering has sometimes been the origin of floods like in Bangkok, Houston or San Francisco Bay, USA (Poland and Green 1962). Damage requires millions of dollars not only to repair damages but also to prevent them.

The first case of generalized subsidence registered in Spain occurred in Murcia, because of a serious drought during the years 1992–95, which reduced the recharge of the aquifer and increased the rate of groundwater withdrawal (IGME 1999).

Subsidence due to decreasing water levels in the metropolitan area of Murcia

The phenomenon of ground consolidation in the city of Murcia has led to the appearance of severe cracking and settlement in buildings. Subsidence is the result of two factors: on the one hand, the nature of the ground in this area, which is made of recent deposits of clay and soft limes filled in with clay–lime backfills in the top layers. On the other hand, the increase in groundwater withdrawal during the 1992–95 drought, which led to a decrease in the water level of a magnitude never before recorded in the city.

Most of the moderate settlement occurring to the buildings in Murcia is related to their own structural problems such as: rotting timber piles, loss of friction in concrete piles or breaks occurring in local sewer systems.

The consolidation of soft superficial deposits is because of two related hydrologic situations: the decrease of the water level in the upper clay layer deposits and also a decrease in the piezometric level in the deep gravel deposits.

The effect of the depletion of the water table is a reduction of interstitial pressure with an increase of effective stress (Terzaghi's law) taking place in consolidation of the ground, provoking as a final result that the pile works at higher load.

The risk prevention management suggested the convenience of the installation of a measurement network,

operated by IGME and the Government of Murcia, to study and follow the phenomena of the subsidence to quantify it and to calibrate the theoretical model.

In 2001, a Project entitled “Surveying and instrumental control of the terrain settlement in the Metropolitan Area of Murcia City” was signed between the IGME (Geological Survey of Spain) and the Government of the Region of Murcia (IGME 2001). The aim of Phase I was to instal an instrumental monitoring network composed by 22 extensometers to measure the subsidence, to analyse the data obtained and to calibrate the model of subsidence previously developed in the Project “Geotechnical Study of Subsoil of the Murcia’s Metropolitan Area” (IGME 2000). These measurements continued through the years 2003–2005 to obtain the evolution of subsidence (Phase II); and in 2007, Phase III began involving improvements in the detector network with the installation of new piezometers and extensometers (IGME 2005).

Geotechnical zonation of Murcia’s metropolitan area

The stratigraphic column was defined from the information provided by boreholes (Fig. 1). The stratigraphic column consists of 5–25 m of clay and soft limes with some intercalated sands up to 10 m thick, all overlaying the gravel substratum.

Gravel and sands at the substratum level constitute the main aquifer from which water had been pumped historically. This water withdrawal and the resulting decrease of interstitial pressure in the overlying soft clays are the main cause of the observed subsidence.

Figure 2 is a geotechnical map covering the Medium Flood Plain of Segura River. It was overlain with data of the depth of consolidated substratum and intercalated sands thicknesses (these sands are not compressible; however, they accelerate the process as they act like a natural drain).

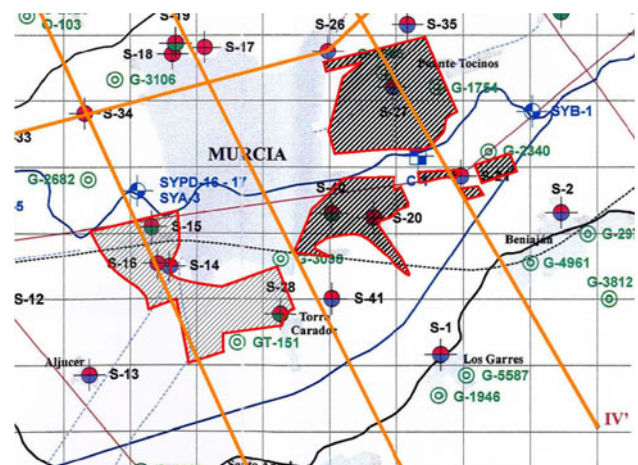
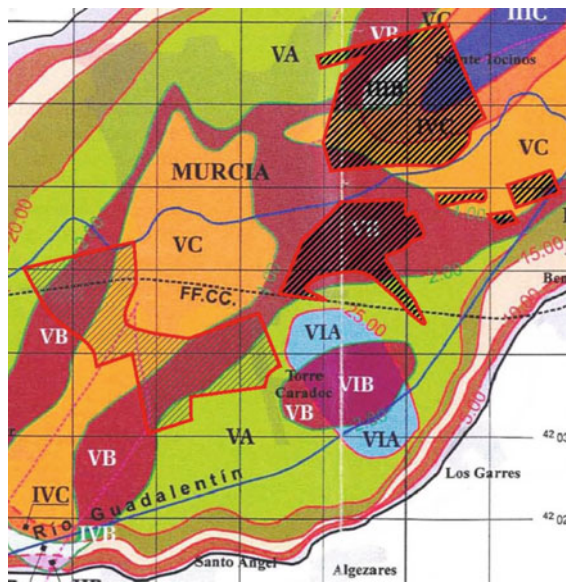


Fig. 1 Situation of boreholes and geological cuts

Fig. 2 Zonation map of the medium flood plain of the Segura River



ZONES		DEPTH OF CONSOLIDATED SUBSTRATUM					
		< 5 m	5-10 m	10-15 m	15-20 m	20-25 m	> 25 m
SAND INTERCALATIONS	< 2 m	IA	IIA	IIIA	IVA	VA	VIA
	2-4 m		IIB	IIIB	IVB	VB	VIB
	4-10 m			IIC	IVC	VC	VIC
	< 10 m						VID

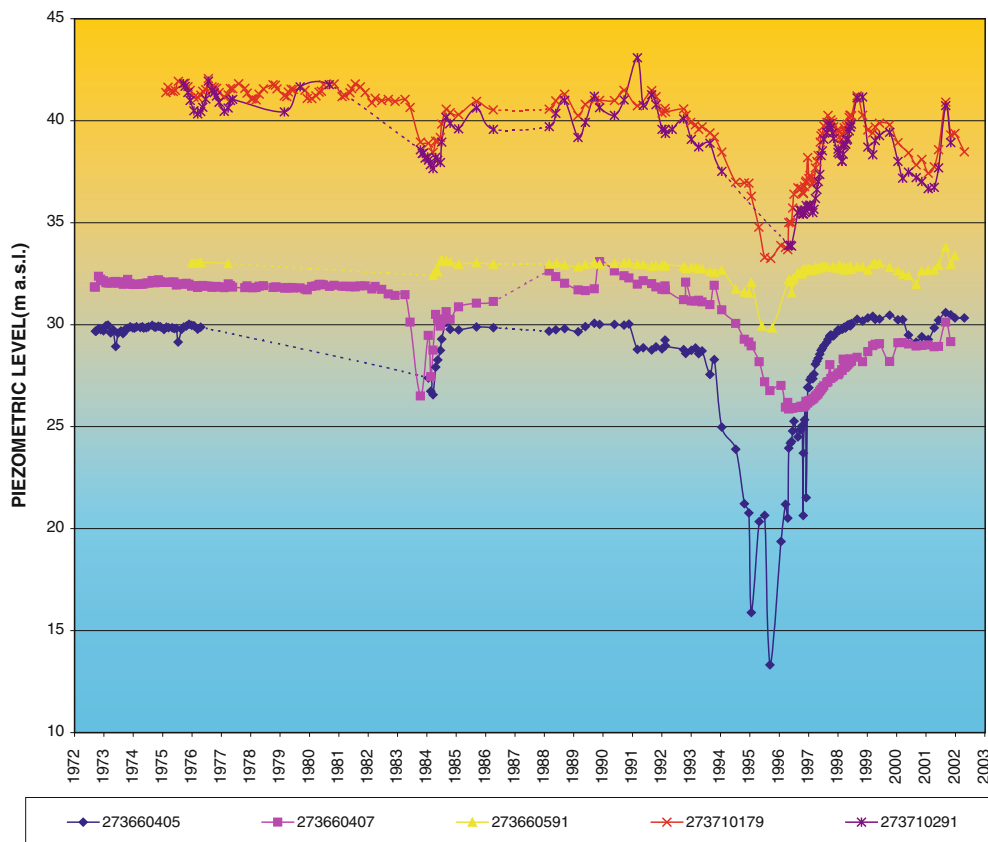


Fig. 3 Piezometric history

Table 1 Results obtained from the extensometer measurements

Extension	Period February 2005–October 2005				Period February 2001–October 2005			
	0–5 m (mm)	0–10 m (mm)	0–15 m (mm)	0–Final (mm)	0–5 m (mm)	0–10 m (mm)	0–15 m (mm)	0–Fin. (mm)
Ei-1	−0.039	−0.382	−0.763	–	−0.826	−2.247	−3.178	–
Ei-2	0.0421	−0.760	−1.157	−1.309	−0.514	−0.277	−0.483	−0.234
Ei-3	−0.740	+0.109	−0.292	+0.214	−1.609	−2.049	−1.959	−0.767
Ei-4	−0.584	−1.429	−2.029	−2.353	−2.173	−3.467	−3.985	−4.136
Ei-6	−0.993	−1.414	–	–	−2.801	−3.556	–	–
Median	−0.46	−0.77	−1.06	−1.15	−1.58	−2.31	−2.40	−1.71
V-1	−2.82	−2.26	–	–	−20.69	−18.01	–	–
V-3	−1.68	−0.99	–	–	−7.68	−5.44	–	–
V-4	−0.59	−2.28	−0.50	–	+13.97	+12.59	+6.65	–
V-5	−7.72	−10.21	–	–	−17.37	−21.35	–	–
V-6	−3.04	−4.41	–	–	−20.41	−19.84	–	–
V-8	−0.77	−0.67	+0.25	–	−11.68	−11.42	−10.04	–
V-13	−6.82	−7.06	−5.91	–	−17.93	−19.82	−16.97	–
V-14	−4.80	−4.41	–	–	−10.49	−9.93	–	–
V-15	−1.24	+0.08	–	–	−5.03	−3.83	–	–
V-17	−0.86	−1.12	–	–	−16.77	−15.26	–	–
Median	−3.03	−3.33	–	–	−11.4	−11.23	−6.79	–

Piezometric history

The piezometric history of the gravel aquifer was developed from information provided by the IGME. This information allowed the study of the evolution of the phreatic levels from 1972 to 2000. Decreases in the phreatic levels larger than 16 m were observed in the region around Murcia in the period between 1992 and October 1995. During the same time period, water level decreases in the city were around 8 m. From October 1995 to October 1997, the water table recovered to previous levels (Fig. 3).

Numerical model

A quantitative study of the process of soil compaction was made of the following parameters:

- Ground settlement (soil, land surface): magnitude and development over time.
- Surface areas affected by settlement: magnitude and evolution over time.
- Evaluation of effective stress and interstitial pressure in the ground and its evolution during consolidation process.

Numerical modelling was done with the finite-elements code Z-SOIL V 4.2., which solves the coupled equations for flow and deformation over time, and allows the calculation of interstitial pressures, stresses and settlements following them, during the process of decreasing piezometric levels.

Instrumental control and survey of land settlement in Murcia's metropolitan area

Extensometer boreholes

To determine the land subsidence rates, 22 boreholes were installed during Phase I.

One of two types of extensometers was installed in the boreholes. Fifteen of them were fitted with rod extensometers with three points of measurement, three anchorages at different depths. The other seven were fitted with incremental extensometers.

In the summer of 2008, during Phase III, 18 new boreholes were instrumented. Nine were fitted with incremental extensometers. Close to each of them, a borehole was equipped as a piezometer and two reference bases with two points of anchorage at 10 and 15 m, acting like rod extensometers. This provided nine new points of measurement during Phase III to achieve a better correlation between settlement and changes in water levels.

Rod extensometers provide information at two or three depths, depending on the points of anchorage, incremental extensometers provide information for each metre.

Extensometer measurements

Table 1 shows the results of the measurement of the extensometers. The data in Table 1, collected during the

Fig. 4 Subsidence between 0 and 10 m deep, period February 2001–October 2005

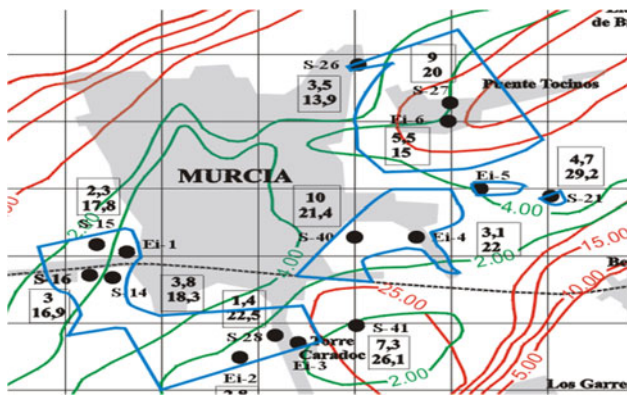
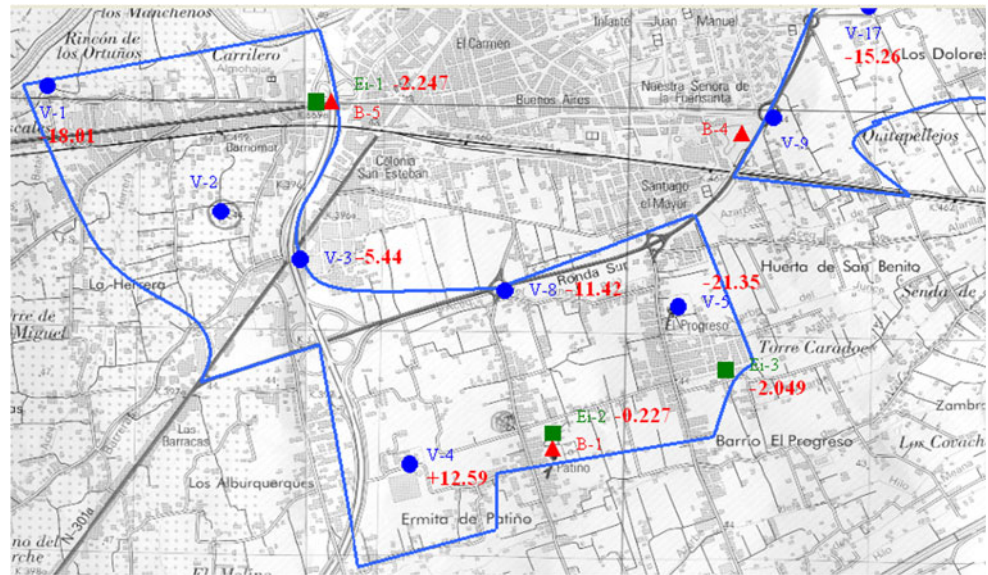


Fig. 5 Lithological map of the area

period February 2001–October 2005, indicates that subsidence is mainly occurring at depths from 0 to 10 m below the ground surface.

Analysis and calibration of numerical model

The final objective was to calibrate the theoretical geotechnical model.

Comparison between the modelled lithological column and the column developed from borehole data

The map in Fig. 4 was created from measurements taken in boreholes during the development of the geotechnical model adopted in a previous study of the Metropolitan Area of Murcia (IGME 2000). It shows the depths of the

incompressible substratum, gravel (red isolines), and the thickness of intercalated sand (green isolines).

The position of boreholes with recovered core performed in Phase II (IGME 2005) are shown on this map. The depth of the substratum (lower number in Fig. 4) and the thickness of intercalated sand (upper number in Fig. 4) are also indicated.

From Fig. 5, the good correlation that exists between the geotechnical model and the measured data of Phase II is remarkable.

Comparison between observed and calculated subsidence

During the summer of 2005, a 1.5-m decrease of the piezometric level was recorded in a 6-month period. The Model was based on a water level decrease of 5 m in a 2-year period.

In Table 2, an extrapolation from the model was made considering the real 1.5 decreasing of water level in a 6-month period.

It can be inferred from Table 2 that the media of settlement obtained from the model for Sector II is 0.42 cm; this value obtained is in a rank between media value enregistered with incremental extensometers (0.16 cm) and rod extensometers (0.67 cm). The same for Sector III of 0.49 cm media value extrapolated from the model is between media value enregistered with incremental extensometers (0.27 cm) and rod extensometers (1.44 cm).

Disparity between incremental and rod extensometers is under study; several factors may be involved such as location and measurement method.

Table 2 Comparison between the decreases calculated with numerical model and measured by extensometers

Piezometric decrease	Modelization	Extrapolated from model	Obtained by monitoring		Observations extensometers			
			5 m	1.5 m	1.5 m		Identification	Length (m)
					Incremental extensometers	Rod extensometers		
Settlement (cm)								
SECTOR II	0.85	0.25	0.31	–	Ei-1	15		
El Carmen	1.94	0.58	0.02	–	Ei-2	21		
Patiño W	1.02	0.30	–	1.80	V-1	10		
	1.38	0.41	–	+0.66	V-4	15		
	1.41	0.42	–	1.00	V-8	10		
	1.63	0.49	–	0.54	V-3	10		
	1.73	0.52	–	–	–	–		
	Maximum	1.94	0.58	1.80	–	–	–	
Minimum	0.85	0.25	+0.66	–	–	–		
Median	1.42	0.42	0.50	–	–	–		
SECTOR III	0.86	0.26	0.07	–	Ei-3	21		
Patiño E	1.84	0.55	0.1	–	Ei-4	21		
Los Dolores	2.31	0.69	0.35	–	Ei-2	10		
PuenteTocinos	0.95	0.28	–	2.13	V-5	10		
	1.1	0.33	–	1.98	V-6	10		
	1.41	0.42	–	1.69	V-13	15		
	1.52	0.45	–	0.99	V-14	10		
	1.5	0.45	–	0.38	V-15	10		
	Maximum	2.31	0.69	2.13	1.52	V-17	10	
Minimum	0.86	0.25	0.07	–	–	–		
Median	1.64	0.49	1.06	–	–	–		

Application InSAR

Radar Interferometry (InSAR) is a remote sensing technique that allows monitoring land surface deformations with millimetre accuracy. The availability of a historical archive of satellite images (available from 1991), the large size of working area (100 km²), the great quantity of observations of deformation (each one 80 m²), and its low cost, all make this technique a complementary tool of traditional geodetic techniques. Urban or arid zones with sparse vegetation are ideal for this monitoring. The IGME is monitoring land subsidence in Murcia with InSAR, which allows:

- Quantification of deformation during the period from 1992 to 1995, by analysis of historical SAR images.
- Identification of possible deformation at the present time and in the future, by acquiring SAR images.
- Calibration of the ZSOIL finite elements deformation model.

Conclusions

- Similar tendency is observed between rod and incremental extensometers.
- Consolidation takes place primarily in the first 10 m below the land surface.
- Based on the experience gained in Phases I and II, Phase III, which began in 2007, included some improvements: InSAR will allow the study of large areas not previously monitored, piezometers close to extensometers to study how water level rates have influence in the extensometers measurements behaviour.

References

- IGME (1999) Estudio geotécnico para el análisis, prevención y corrección de la patología constructiva derivada del cambio en las condiciones del subsuelo en la ciudad de Murcia

- IGME (2000) Estudio geotécnico del subsuelo Área Metropolitana de Murcia
- IGME (2001) Seguimiento y control instrumental de asentamientos del terreno en el Área Metropolitana de Murcia
- IGME (2005) Continuación en el seguimiento y control instrumental de asentamientos del terreno en el Área Metropolitana de Murcia. Fase II
- Jachens RC, Halzer TL (1982) Differential subsidence mechanism for earth fissures near Casa Grande. Geological Society of American Bulletin 93, Arizona
- Lockwood MG (1954) Ground subsides in the Houston Area. Civil Eng ASCE 24:6
- Pincharoen C (1977) Groundwater and land subsidence in Bangkok. IAHS Pub. 121, Thailand
- Poland JF (1984) Guidebook to studies of land subsidence due to groundwater withdrawal. UNESCO
- Poland JF, Green JH (1962) Subsidence in the Santa Clara Valley (California). In: A progress report, U.S. Geol Survey Water Supply Paper 1619-C
- Poland JF, Lofgren BE, Ireland RL, Pugh RG (1975) Land subsidence in the San Joaquín Valley (California). In: U.S. Geological Survey Professional Paper 437-H
- Takeuchi S, Kimoto S, Wada M, Shiina H, Mukai K (1969) Geological and Geohydrological properties of the land subsidence area. I.A.S.H. UNESCO