RELATIONSHIP BETWEEN PIEZOMETRIC LEVEL AND GROUND DEFORMATIONS MEASURED BY MEANS OF DINSAR IN THE VEGA MEDIA OF THE SEGURA RIVER (SPAIN)

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ABSTRACT:

Differential SAR Interferometry (DInSAR) is a remote sensing method with the well demonstrated ability to monitor geological hazards like earthquakes, landslides and subsidence. Among all these hazards, subsidence involves the settlement of the ground surface affecting wide areas. Frequently, subsidence is induced by overexploitation of aquifers and constitutes a common problem that affects developed societies. The excessive pumping of underground water decreases the piezometric level in the subsoil and, as a consequence, increases the effective stresses with depth causing a consolidation of the soil column. This consolidation originates a settlement of ground surface that must be withstood by civil structures built on these areas. In this paper we make use of an advanced DInSAR approach - the Coherent Pixels Technique (CPT) [1] - to monitor subsidence induced by aquifer overexploitation in the Vega Media of the Segura River (SE Spain) from 1993 to the present. 28 ERS-1/2 scenes covering a time interval of about 10 years were used to study this phenomenon. The deformation map retrieved with CPT technique shows settlements of up to 80 mm at some points of the studied zone. These values agree with data obtained by means of borehole extensometers, but not with the distribution of damaged buildings, well points and basements, because the occurrence of damages also depends on the structural quality of the buildings and their foundations. The most interesting relationship observed is the one existing between piezometric changes, settlement evolution and local geology. Three main patterns of ground surface and piezometric level behaviour have been distinguished for the study zone during this period: 1) areas where deformation occurs while ground conditions remain altered (recent deformable sediments), 2) areas with no deformation (old and non-deformable materials), and 3) areas where ground deformation mimics piezometric level changes (expansive soils). The temporal relationship between deformation patterns and soil characteristics has been analysed in this work, showing a delay between them. Moreover, this technique has allowed the measurement of ground subsidence for a period (1993-1995) where no instrument information was available.

Keywords: DInSAR, CPT, subsidence, piezometric level, overexploitation

INTRODUCTION

Subsidence implies the settlement of ground surface over a wide area due to natural or anthropic causes [2]. Although, in general, this phenomenon does not cause mortal victims, it implies important economic losses, mainly in urban areas. Unfortunately, the damages caused by ground subsidence exhibit a temporal shift with respect the start of the ground subsidence process. The study of this kind of phenomena implies its monitoring to determinate the extension of the affected area, the settlement or uplift velocities, their mechanisms, the critical moments of acceleration of the soil consolidation process, and the evaluation of the effectiveness of the adopted correction and/or mitigation measures. Usually, the problem is studied at the terrain surface level, measuring the existing deformations by means of conventional topographical, geodetic, photogrammetric, instrumental or remote sensing techniques [3]. Recently, Differential SAR Interferometry (DInSAR) has been applied to the monitorization of terrain motions due to geological and/or geotechnical problems affecting wide areas.

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In this work we apply an advanced DInSAR technique called Coherent Pixels Technique (CPT) to study the subsidence of the Vega Media of the Segura River aquifer during 1993-2004 period. The Vega Media of the Segura River (SE Spain) has suffered this type of process due to detritic aquifer exploitation during 1992-95 drought period. Piezometric levels fell between 5 and 8 meters [4] and, consequently, an estimated consolidation of soft superficial soil levels of 1 to 8 cm took place [5]. Damages in more than one hundred buildings were reported and they were valuated in more than 50 million euros [6].

GEOLOGICAL AND GEOTECHNICAL SETTING

The monitored zone corresponds to the metropolitan area of the city of Murcia that occupies the flood plain of the Segura River, also known as the Vega Media. The study area is located in the oriental sector of the Betic Cordillera. A compressive stress field has acted since the Upper Miocene in this sector and has led to the development of a basin bounded by two active faults, the Lorca - Alhama, to the north, and the Carrascoy - Bajo Segura, to the south [7]. The sedimentary record of the basin has been deformed as it has been deposited, creating a broad syncline in which progressively younger sediments have been deposited. The basement of the basin is made up of old (Permian and Triassic) deformed materials corresponding to the Internal Zones of the Betic Cordillera. These materials also crop out along the edge of the Segura River Valley (Fig. 1).

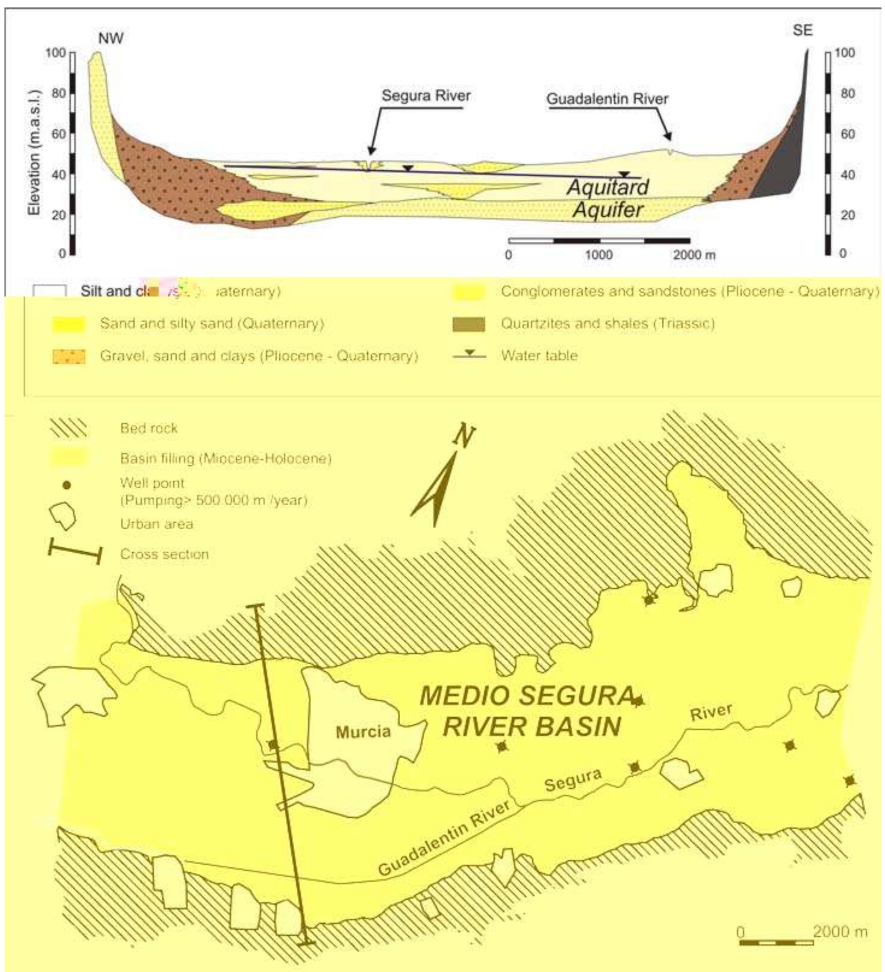

Fig. 1. Simplified geological map and cross section of the Vega Media of the Segura River (based in [4]).

The basin fill consists of Upper Miocene to Quaternary sedimentary rocks that can be divided into three units (Fig. 1). Older materials (Upper Miocene) mainly consist of a thick sequence (more than 600 m) of marls [6]. Above them, pliocene-quaternary rocks consist of marls and clays interbedded with several levels of conglomerates and sandstones, deposited in a continental environment. The overall thickness of these materials is about 150 m, although they can reach 200 m in some places [4]. At surface level, recent continental (meander, channel, oxbow lakes, flood plain, alluvial fans, etc.) sediments are found. Silts and clays are abundant in the flood plain and oxbow deposits, while sand is common in channel areas and in the alluvial fans formed in the relief features around the valley. The thickness of the recent sediments varies between 3 and 30 m. Anthropic fills can be also found at surface level in certain places.

From a hydrological point of view, two units with aquifer properties have traditionally been identified [4]. The first, or surface aquifer, consists of recent sediments. Since fine sediments are very abundant, its hydrological properties are poor (vertical and horizontal permeability varying between 0.03 - 0.1 m/day and 0.01 – 5 m/day, respectively) and it is scarcely exploited. The second unit, or deep aquifer, is located immediately below the recent sediments. It consists of a 10 to 30 m thick sequence of conglomerates with a matrix of variable nature (sand, silt and clays) which is part of the Pliocene – Quaternary sedimentary rocks. The horizontal and vertical permeability of this aquifer are typically between 10 - 100 m/day and 1 - 50 m/day, respectively [4]. This level of conglomerates is found at the top of the Pliocene – Quaternary sedimentary rocks. The piezometric level of the deep aquifer is high, typically situated a few metres below ground level, and completely saturating most of the surface sediments. The recent sediments, or materials that constitute the surface aquifer, are the most compressible in the zone. They consist of a layer of medium to soft sediments, susceptible to suffering consolidation due to variations (increases) in the effective stresses acting on them. On the contrary, the underlying conglomerates and marls are more rigid and represent the geotechnical substratum of the zone, used as the support level for deep foundations. Because of their rigidity, no significant deformations due to effective stresses increase are expected [5].

METHODOLOGY

Interferometric phase ($\Delta\psi_{int}$) obtained by combining two SAR images can be expressed for a two pixels' relation as [8]:

$$\Delta\psi_{\mathrm{int}} = \Delta\psi_{flat} + \Delta\psi_{topo} + \Delta\psi_{mov} + \Delta\psi_{atmos} + \Delta\psi_{noise} \quad (1)$$

where: $\Delta\psi_{flat}$ is the flat earth component that is related with range distance and can be calculated easily, $\Delta\psi_{topo}$ is the topographic phase component that can be removed using a external Digital Elevation model (DEM), $\Delta\psi_{atmos}$ is the phase component related with atmospheric artefacts, $\Delta\psi_{noise}$ is the degradation factor of interferometric phase, and $\Delta\psi_{mov}$ is the interferometric phase term due to ground displacement between two SAR images, which is measured along the Line of Sight.

Conventional interferometric techniques allow us to combine two SAR images to calculate ground motions, which incorporate an error term due to noise and atmospheric artefacts that should be removed (Eq. 1). Advanced techniques are more accurate because they allow isolating the phase term due to displacements. The CPT technique [1] [8] assumes that the deformation component of the differential interferometric phase can be broken down into two phase terms, one due to linear deformation and another due to non linear deformation. The retrieval of the linear term includes the estimation of both the DEM error and the mean velocity deformation. These are calculated by adjusting a model function applied only over those pixels' relations of the scene that show good interferometric coherence along time. The non-linear term is estimated by applying a spatial-temporal filtering to extract the contribution of atmospheric artefacts and the low and high-resolution components of the non-linear deformation. Atmospheric isolation is possible because of the different behaviour of non-linear movement with respect to atmospheric artefacts in time and space. A more detailed description of the CPT technique can be found in [1] and [8].

RESULTS

28 SLC SAR images obtained by ERS-1 and ERS-2 satellites have been used to analyze the subsidence of the study area. The images were acquired between April of 1993 and October of 2004. A 10 x 10 Km area centred in Murcia city has been selected, using those interferograms whose spatial baseline is smaller than 50 meters, temporal baseline lower than 1500 days, and Doppler centroid difference lower than 0,3. A total number of 26 interferograms has been found. Their final resolution has been degraded to 100 x 100 m due to the employed averaging multilook of 25 x 5 pixels. The cancellation of the topographic component was carried out by using an external DEM.

The obtained maximum deformations are close to 8 cm, although average values are between 2 and 6 cm, being concentrated in the central sector of the valley, where soft sediments depth is higher. On the contrary, deformations are smaller or even null in the margins of the valley, where there are undeformable rocks and cemented alluvial fans. Extensometric measures taken between February 2001 and December 2003 [9] have been used to validate the results. It can be seen that differences between extensometric and DInSAR measurements are less than 3 mm for available data except to for one of the points, whose difference is 12 mm (Fig. 2). The observed differences can be explained partially by the size of the pixels. DInSAR measures deformation of the dominant targets located in the 100 x 100 m pixel. So, when deformation is heterogeneous inside the pixel (different for every coherent target) point extensometric measure differs from DInSAR measure for the whole pixel. Another reason of the observed differences is that extensometers only measure deformations occurring along soil column traversed by the device while DInSAR measure deformations of the whole soil column.

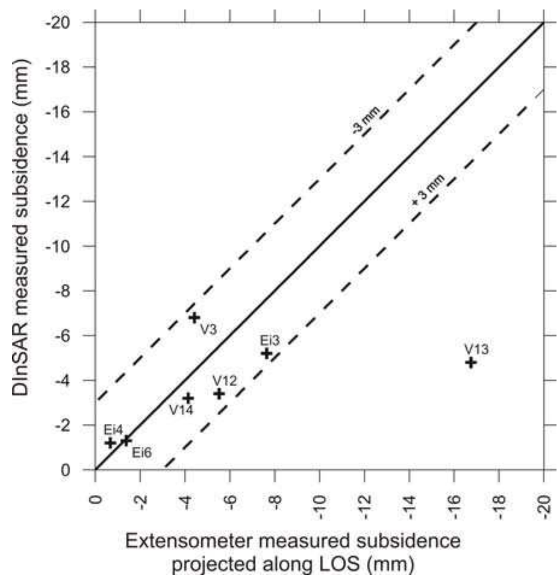

Fig. 2. Comparison between CPT results and extensometer measurements.

Three main deformation behaviours, that are representative of wide areas of the study zone, have been distinguished [10] (Fig. 3): (1) Deformable areas located in the valley and composed of fine sediments that fill the valley; (2) non deformable areas composed of old materials located in the margins of the valley (Miocene-Pliocene alluvial fans, tertiary shales and carbonated rocks); and (3) swelling soils that mimic the piezometric level evolution and are located on the SW of the study area. Every one of these behaviours shows a narrow relationship with the trends observed in the temporal evolutions of the piezometric level and also agree with local geology [10].

The identified behaviour type (1) indicates that soil consolidation starts when piezometric level falls and continues in time until the soil stresses do not recover its initial stresses state, that is, consolidation does not cease until piezometric level recuperates its previous level. If the equilibrium state is not restored, consolidation velocity can vary, but deformation does not cease. On the other hand, the behaviour type (2) shows that soil does not deform under piezometric level changes because it is low or non deformable. Finally, the behaviour type (3) corresponds to lightly swelling soils, where deformations depend on moisture content, which is regulated by ups and downs of water level.

CONCLUSIONS

CPT technique can be used for measuring deformations in wide areas with high efficiency. It can be complemented with other kind of measures (extensometers, GPS, topography, etc.) to validate the results obtained with DInSAR and to obtain information of points that are not coherent. In the Vega Media of the Segura River, the results obtained agree with extensometer measurements and show a close relationship with piezometric level variations and local geology. Concretely, three main kinds of behaviours have been recognized. The first corresponds to deformable soils (mixture of silts, sands and clays at different proportions) where piezometric lowering induces consolidation processes. The second corresponds to non deformable areas (alluvial fans, carbonated rocks, etc.) where piezometric variations do not induce deformations. Finally, there exists swelling soil behaviour where deformations mimic the ups and downs of piezometric level.

An important advantage of this technique is that it has allowed measuring the subsidence magnitude that affected the Vega Media of the Segura River once the maximum consolidation process was produced. It has to be considered that the first damages were detected during 1995, and the process was not instrumented until 2001. So, the presented results suppose a very valuable information about the process that affected this area before it was instrumented.

Among the advantages of this technique, and by extension, of SAR inteferometry, we can emphasize that it allows to study the evolution of a phenomenon that affects wide areas of territory at low cost (in comparison with another commonly used techniques). Also, it allows to obtain a progressive monitoring of the deformation process (subsidence) along time, which facilitates the decision-taking for the planners.

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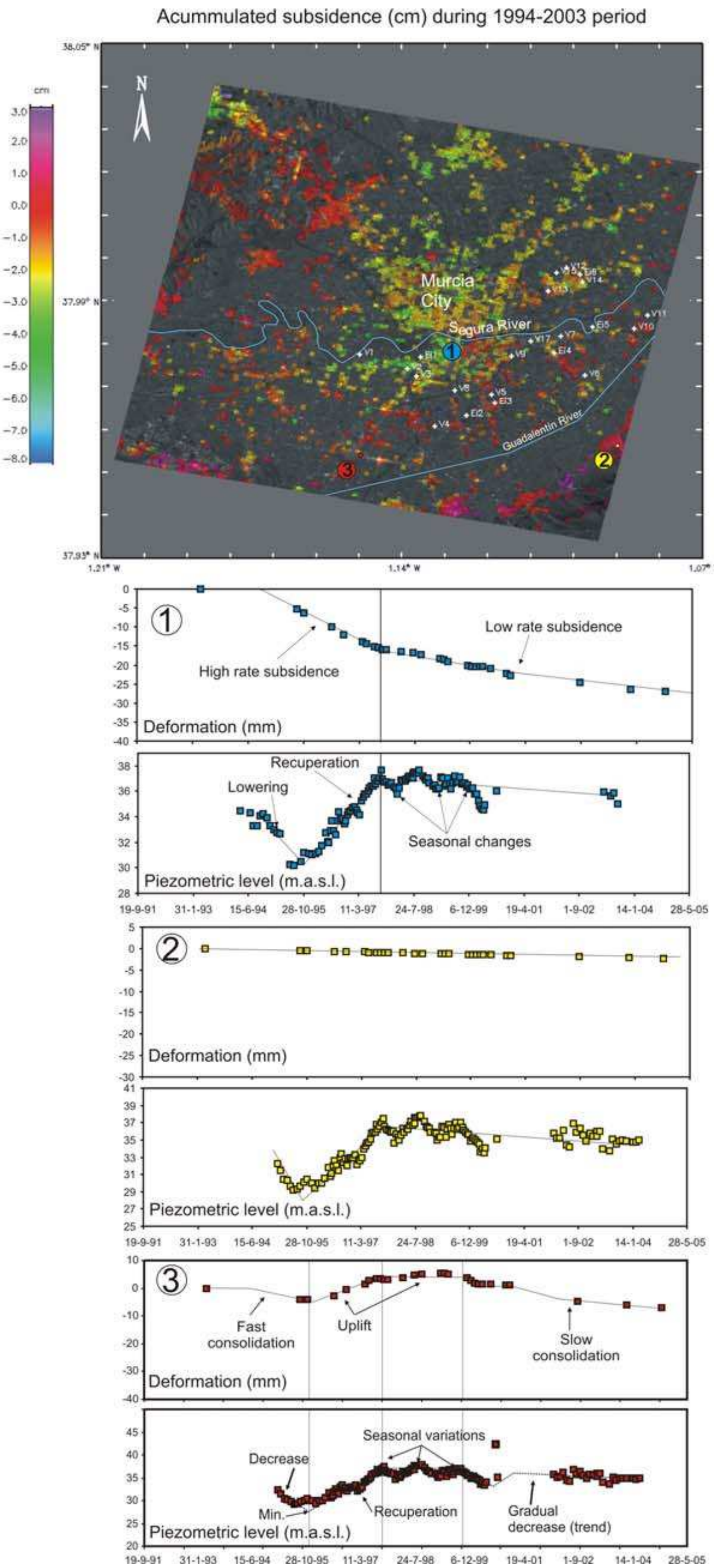

Fig. 3. Evolution of subsidence measured by means of CPT and piezometric level in three representative boreholes.