Two-dimensional coupled numerical modelling of subsidence due to water extraction at the Lower Llobregat River, Spain

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Abstract A Differential Interferometry of Satellite Radar (DinSAR) analysis has detected relatively strong subsidence at the St Feliu del Llobregat municipality west of Barcelona City (average maximum velocity of 0.7 cm/year for the period 1993–2006). Compilation of geological information and geotechnical logs, well piezometric measurements, and the performing of two electrical resistivity tomography (ERT) surveys allowed us to establish a geological–hydrogeological model of the site. A shallow saturated compressible clay layer (thicker where the most intense terrain deformation occurs), overlays sandy-silty gravels. Both units contain the unconfined Llobregat River upper aquifer. A simplified numerical coupled 2D-FLAC model, with the existing conditions at the site, permitted simulation of the surface deformation measured by DinSAR. Although refinements to the model, by changes in the clay layer geometry and water volume extraction rates, are still needed, the calibration of the numerical model allows the prediction of deformation under one specific water extraction rate.

Key words SAR Differential Interferometry; subsidence; Lower Llobregat River, Spain; water flow and strain-stress coupled models; FLAC-2D

INTRODUCTION

As result of a collaborative effort between the Geological and Cartographic Catalonian Institutes (IGC and ICC, respectively) in a project monitoring terrain movements with Differential Interferometry of Satellite Radar images (DinSAR), seven sites with subsidence within the Catalonian territory were identified during the years 1993–2006. Two of these sites were already known to be related to underground mining activity. For the rest of these subsidence sites, investigations to identify the possible subsidence mechanisms were carried out by compiling geotechnical, geological and hydrogeological information as suggested by the USGS subsidence database (Marturia & Concha, 2008). Preliminary results have shown that these sites are located mainly on sedimentary basins with a large density of water extraction points (ACA, 2008) and industrial land use. Here, we present the results for the Sant Feliu del Llobregat pilot site, Fig. 1, where detailed investigations were carried out by calibration of a first simplified 2-D-coupled numerical model.

GEOLOGY AND HYDROGEOLOGY AT THE MAXIMUM SUBSIDENCE AREA

The study zone is located over Quaternary sediments characterized by fluvial terrace deposits that laterally change to alluvial and colluvial deposits. Specifically at the maximum subsidence zone, consolidated and compacted Neogene deposits are covered by Quaternary deposits. These deposits are representative of the Qt1 unit, the youngest Llobregat River terrace, Fig. 1, where two different layers can be differentiated: a lower sandy-silty gravel covered by an upper layer of silty clay of variable thickness (max. 20 m). Both units contain the non-confined upper Llobregat River aquifer. The ERT surveys, Fig. 2, define the geometry of the layers and show that both are saturated. The water head variation (Δh) at this area is about three metres, Figs 1 and 3.

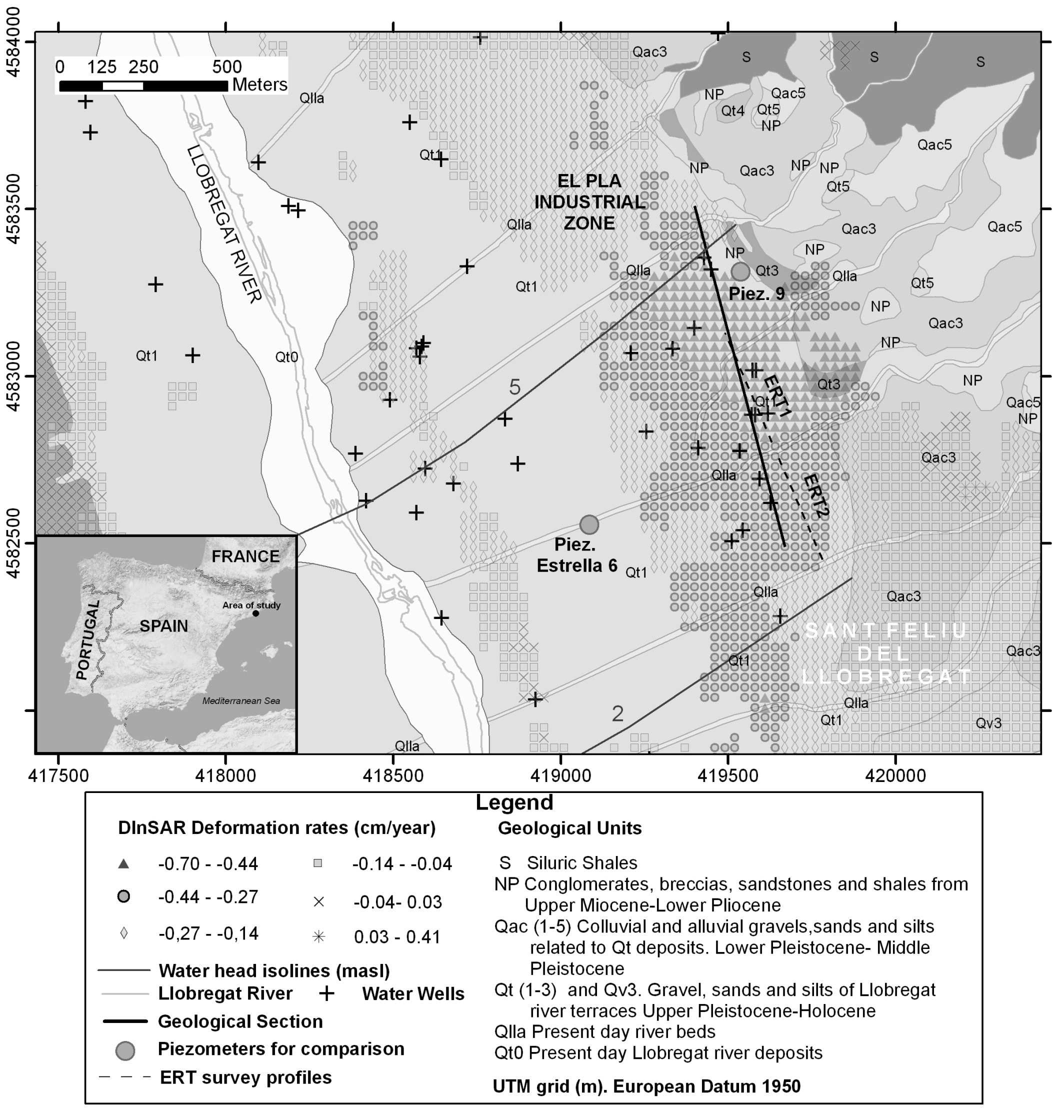

Fig. 1 Location of the study area and geological map (ICC, 2006). Location of water wells, piezometers (ACA, 2008), water head isolines (ICC, 2006), ERT surveys and simplified geological section used for the numerical model.

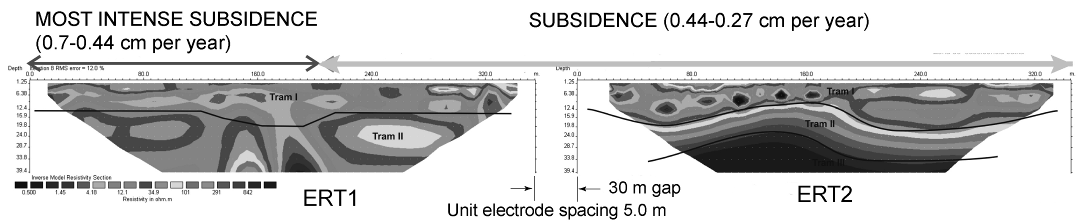

Fig. 2 Results of the ERT1 and ERT2 surveys (Gabàs *et al.*, 2009) Location is shown in Fig. 1.

FLAC SIMPLIFIED 2D NUMERICAL MODEL

A simplified numerical model was built considering the larger thickness of the shallow silty clay deposit (20 m) in a 1060-m long topographic profile, parallel to the flow direction, Fig. 1. Since variations of the phreatic level take place only in the upper silty clay layer, the thickness of the

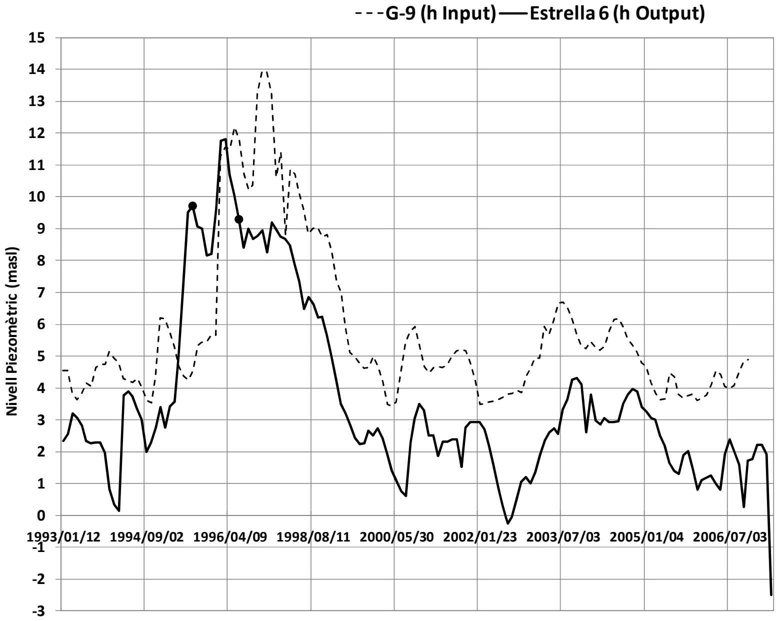

Fig. 3 Water head measurements at the model profile ends (piezometers G9 and Estrella 6, Fig. 1). Points show the water head difference in time used to calculate a first approximation of extraction water rates

Table 1 Laboratory geotechnical parameters for the two geological units used in the numerical model.

Property	Upper compressible layer	Lower silty gravelly sands
E (MPa)	25.4	10.8
Poisson ratio	0.4	0.33
Dry density (kg/m^3)	1590	1700
Friction (°)	24.5	30
Cohesion (kPa)	23.5	4.9
Porosity	0.5	0.7
Permeability (m/s)	1×10^{-9}	6×10^{-5}

lower layer was considered homogeneous (30 m). Geotechnical and hydrological laboratory parameters (IGC, 2008) for both units are shown in Table 1. The closest wells along the profile are included in the model as points of water extraction at the maximum depth of the well. Since rates of water extraction are not known at each well, the variation of the phreatic level along the profile in a 395-day long period, Fig. 3, was used to calculate a first approximation of water extraction rates. The value obtained was applied equally at each well along the profile (0.16 m^3/day), for pumping during a 15-day period, turning off pumps and step calculations for 15 days more to evaluate the response of the layer. Figure 4 shows the finite difference grid and mechanical boundary conditions.

RESULTS AND DISCUSSION

The numerical model reproduces the shape of the profile and magnitude order of the DinSAR deformation profile within the area of maximum subsidence for a 15-day period of continuous pumping at 0.16 m^3/day per well and after 15 days of restoration. Figure 4 shows the deformation

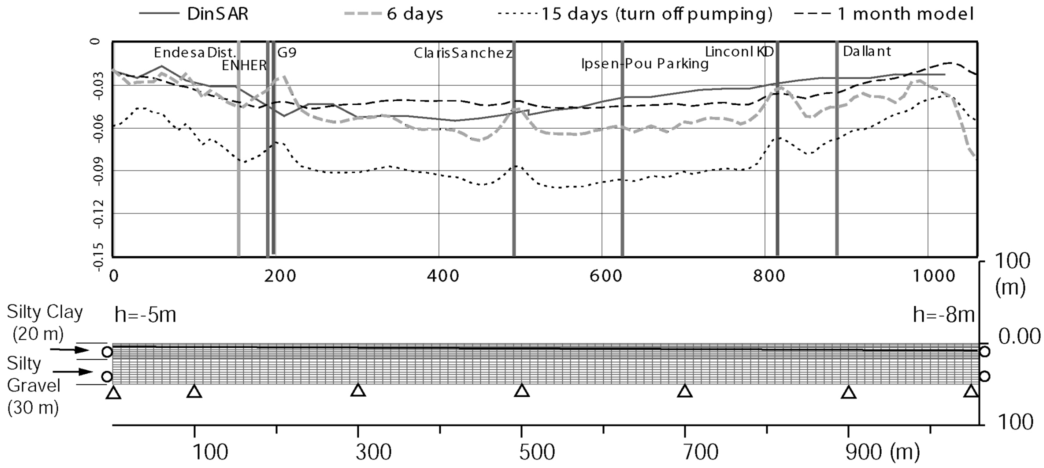

Fig. 4 Finite difference grid, mechanical boundary conditions and water head gradient (h) along the simplified geological model profile. Upper graphic shows the results of different deformation stages at the topographic surface for 1-month long calculation period. For comparison the DinSAR deformation curve was calculated for the same time period. Vertical lines mark the location of water wells.

curves for 6, 15 (turning off pumping) and 30 days. Refinements of the model might include the detailed geometry of the upper silty-clay layer, directional permeability and registered water extraction rates for each well. Sensitivity analysis of this last parameter might aid evaluation of the water extraction rates critical for subsidence to cause structural damages in buildings and soil cracking, and to establish pumping rates controls for specific environmental laws.

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