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Subsidence damage assessment of a gothic church using Differential Interferometry and field data

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Abstract

The Santas Justa and Rufina gothic church (XIV century) has suffered several physical, mechanical, chemical and biochemical types of pathologies along its history: rock alveolization, efflorencescences, biologic activity and capillary ascent of ground water. However, during last two decades a new phenomenon has seriously affected the church, the ground subsidence caused by aquifer overexploitation. Subsidence is a process that affects the whole Vega Baja of the Segura River basin and consists on the gradual sinking of ground surface caused by soil consolidation due to a pore pressure decrease. This phenomenon has been studied by means of Differential SAR Interferometry (DInSAR) techniques providing settlements up to 100 mm for the 1993-2009 period for the whole Orihuela city. Although no DInSAR information is available for the church due to the loss of interferometric coherence, a spatial analysis of the deformations affecting the neighbour areas jointly to field reported information has allowed to better understand the mechanisms that affect the Santas Justa and Rufina church, showing the potential interest of these remote sensing techniques for supporting building forensic analyses.

Keywords: Forensic analysis, DInSAR, ground subsidence, gothic church, historic building monitoring

Research highlights: Santas Justa and Rufina has suffered several kinds of pathologies along its history > The last two decades the church has been affected by ground subsidence processes due to aquifer overexploitation > Subsidence has seriously affected the church > The joint use of DInSAR techniques and field observations has permitted to better understand subsidence pathologic processes affecting the church

1. Introduction

Subsidence due to water level withdrawal is a well-known phenomenon that implies the ground settlement due to an increase in soil effective stresses caused by piezometric level decrease. This phenomenon is not spatially uniform due to changes in soil properties and spatial variation of deformable soil thickness and piezometric levels, causing differential settlements and distortions affecting buildings founded on ground surface. The measurement of evolution and distribution of these settlements is necessary in order to adopt the appropriate actions to be corrected or minimised. During last years, Differential SAR interferometry (DInSAR) has become a very useful tool for subsidence study. This technique has been specifically useful for study urban areas as México city (Osmanoğlu et al., 2010), Rome (Stramondo et al., 2008), Lisbon (Heleno et al., 2011), París (Fruneau et al., 2005) among others. Furthermore, a more specific monitoring of structures affected by ground subsidence has been performed by Herrera et al. (2010) and Bru et al. (2010) in the city of Murcia (Spain) affected by subsidence, allowing to successfully understand deformational behavior of some structures. In this work, a forensic analysis of the Santas Justa and Rufina church (Figures 1 and 2), located in Orihuela (Alicante province, Spain, Figure 3) using DInSAR is performed jointly with in situ observations data. The Santas Justa and Rufina church was built in the Gothic style in the XIV century and was declared a Spanish National Monument in 1971. Throughout its history, the structure has been repaired several times after suffering the results of seismic movements, fires, etc. In the last two decades, a new phenomenon has appeared that could affect the building’s structural integrity. A series of long-term droughts in South-East Spain jointly with the aquifer overexploitation has caused a high piezometric level descent that has increased the soil effective stresses causing a consolidation process that is manifested on ground surface as settlements. These settlements have affected the Santas Justa and Rufina church causing several damages. The field data, mainly geotechnical data and in situ observations, jointly with DInSAR data has allowed to diagnose the problems affecting the church.

The paper is organized as follows. Section 2 describes Santas Justa and Rufina church principal structure characteristics. Available information and previous works conducted in the church are briefly described in Section 3. Section 4 is devoted to define the geological and geotechnical setting of the study area. Section 5 includes an explanation of damages observed during field works in the church and section 6 is dedicated to subsidence measurements obtained using DInSAR. Then, a diagnosis is performed in section 7 using all previously described information. Finally, section 8 presents the main conclusions.

2. Description of the gothic church

The Santas Justa and Rufina church, declared a Spanish National Monument in 1971, is located in Orihuela (Alicante province, Spain)(Figure 1). It is a Catholic church built in the XIV century and reformed in the XVI and XVIII centuries, presenting both Gothic and Baroque influences. It consists of a main body with lateral chapels located between the counterforts (Figures 1b and 2). Among all lateral chapels there are two higher chapels, San José chapel, located at the NW of the church, and La Comunión chapel, placed at the SW. There are two doors, the main located at the west façade (Figures 1a and 2), and a lateral door (Evangelio door) placed at north façade (Figures 1c and 2). The sacristy, with a square plant, and the antesacristy, with a rectangular plant, are sited at the SE part of the church. Finally, the bell tower found at the north of the church reaches a height of 35.5 m (Figure 1a). The entire building is built of masonry with bricks and ashlars and is directly founded over silts and clays overlaying the church that will be described in detail on section 4.

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Figure 1. Photograph of the Santas Justa and Rufina church: (a) North-west corner. Notice the main door and the bell tower. (b) Main body. Observe the main chapel. (c) North façade with the Evangelio door. See location of these elements on Figure 2.

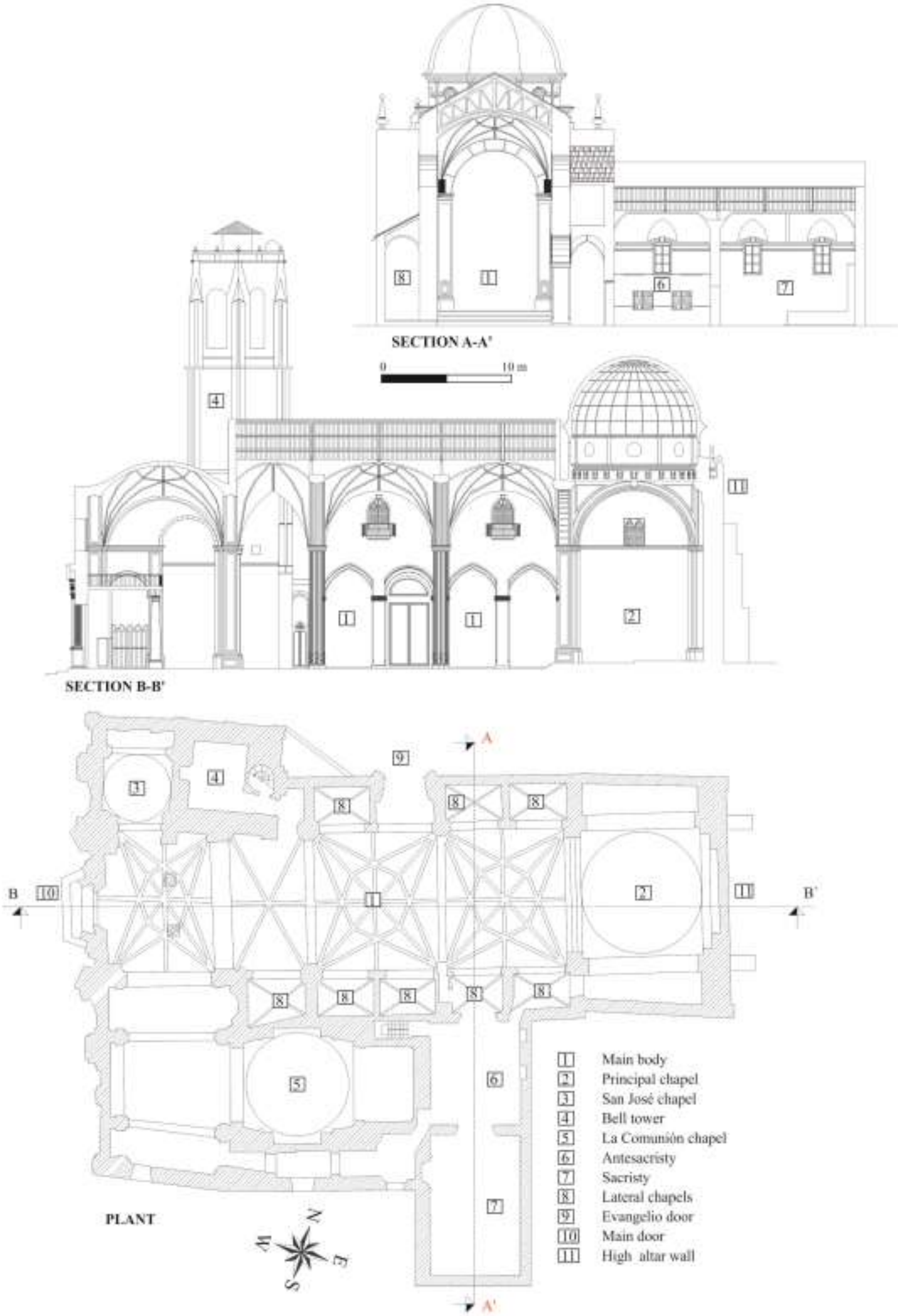

Figure 2. Cross sections and plant of the Santas Justa and Rufina church.

3. Available information and previous works

The Vega Baja of the Segura River has suffered subsidence processes due to groundwater withdrawal, at least since first years of 90's decade, as showed in several news related with important settlements on the west end of Orihuela city. Moreover, a lot of studies have been performed on this area in order to measure subsidence and its relationship with piezometric levels variation. Tomás et al., (2007) studied subsidence from 1993 to 2001 in the Vega Baja of the Segura River using DInSAR techniques measuring values up to 70 mm for the Orihuela city and up to 50 mm for the church neighbourhood. Tomás et al. (2010) contrasted subsidence data for 1993-2009 period obtained by means of DInSAR techniques with subsidence triggering and conditioning factors. Measured settlements for this period were up to 100 mm for the whole urban area and up to 80 mm for the Santas Justa and Rufina church vicinity. Ivorra et al., (2010) has studied the incidence of soil subsidence on the dynamic behaviour of a Santa Justa y Rufina bell tower.

Historical information of the church is available on parochial archives since the church construction. They include a big amount of data about the church in great detail. However, most of the historical information provided by parochial archives is referred to the modifications and maintenance works performed along the time. Several geotechnical reports of the Orihuela city are available. Three of them are focused on the church under study, although unfortunately only one is available. The available geotechnical report was performed specifically for studying the church pathologies on 2007. This geotechnical report includes three boreholes and useful information about the lithology and the geotechnical properties of soil that are summarized in section 4.

4. Geological and geotechnical characterization

4.1. Geological setting

The Vega Baja of the Segura River (VBSR) is located in the more oriental sector of the Betic Cordillera. The study area constitutes a monoclinal structure essentially controlled by the strike–slip Crevillente Fault Zone at the N that represents the convergence of two main structures of the Betic Cordillera: the Cádiz–Alicante Fault System (Sanz de Galdeano, 1990) and the Trans-Alborán Shear Zone (De Larouziére et al., 1988).

The Mesozoic basement of the basin consists of carbonate and evaporitic rocks from the Betic External Zones protrude at the N and E area of the study zone (Delgado et al, 2002). The Bajo Segura Basin is filled by Neogene–Quaternary sediments (Figure 3).

The valley filling is composed on Holocene sediments at the ground surface beyond Pleistocene sediments deposited by River Segura depositional activity, whereas the eastern zones towards the Mediterranean Sea are occupied by littoral and lagoonal sediments (Delgado et al., 2002). Anthropic deposits can be also found at certain points in the valley generally related with urban areas. Recent sediments are the most compressible ones in the area and the most problematic from a geotechnical point of view.

The study area belongs to the so-called "Guadalentín–Segura Quaternary aquifer System N° 47" (IGME, 1986), an aquifer characterized by two units: a) a surface unconfined aquifer unit with a low conductivity composed by fine sand and silts deposited by the recent activity of the Segura River and coastal processes (towards the E of the zone) whose water table is found a few meters below the ground surface. b) A second unit formed by gravels, usually interbedded with marls that constitutes a confined aquifer with greater hydraulic conductivity than the superficial aquifer (DPA-ITGE, 1996). The upper aquifer is the most scarcely exploited.

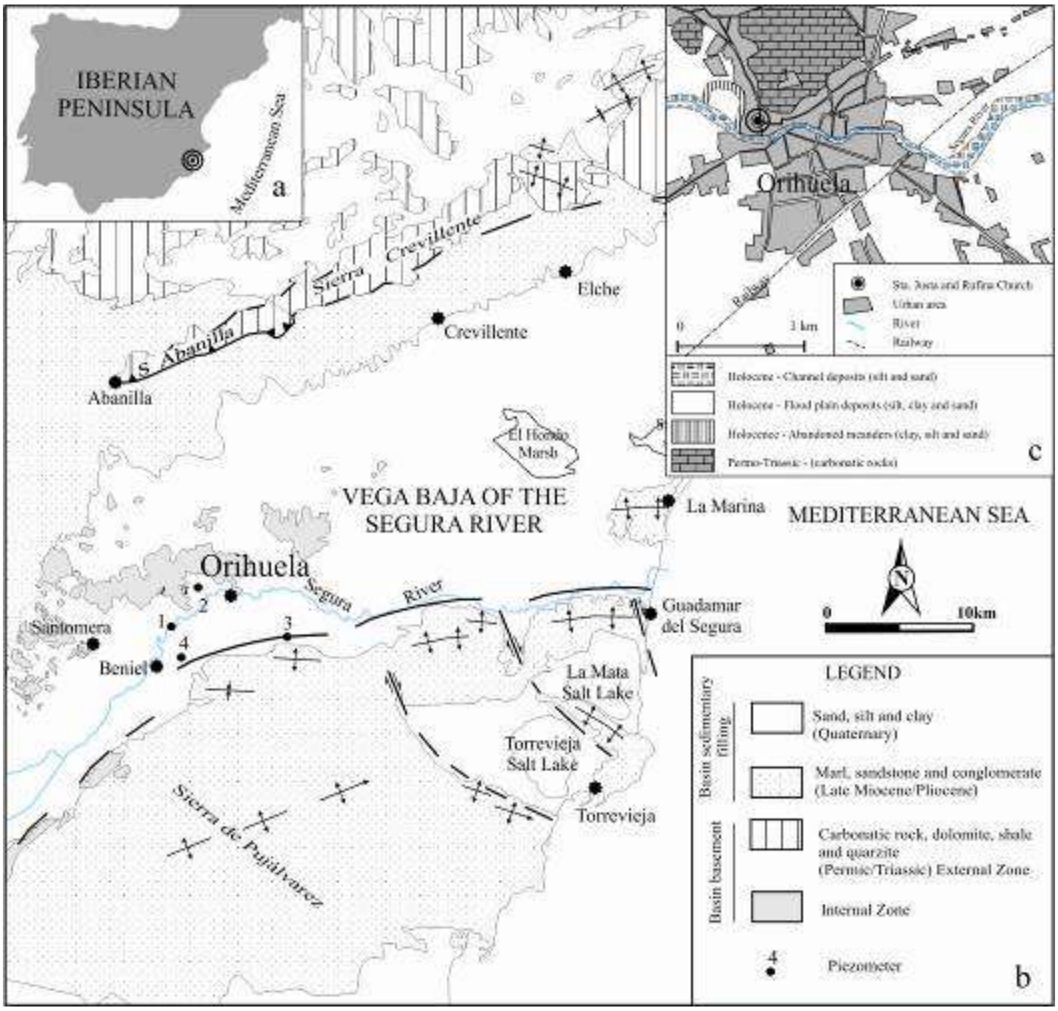

Figure 3. Location and geological setting of the city of Orihuela and the Santa Justa and Rufina Church.

4.2. Geotechnical setting

Delgado et al. (2002) made a geological-geotechnical characterization of the Vega Baja of the Segura River basin based o stratigraphic and geotechnical information. This model shows that sedimentary rocks, that constitute the geotechnical substratum, outcrops on the edges of the valley and are also found at certain depths, varying between 0 to 45 m towards the west, where the town of Orihuela is located. Sediments located above this basement are characterized by moderate to high compressibility, with compression indexes (Cc) varying from 0.07 to 0.29 (Delgado et al., 2002; Tomás et al., 2010) and with an average value of 0.18. These sediments are the most compressible ones in the zone and as a consequence the most problematic from a geotechnical point of view.

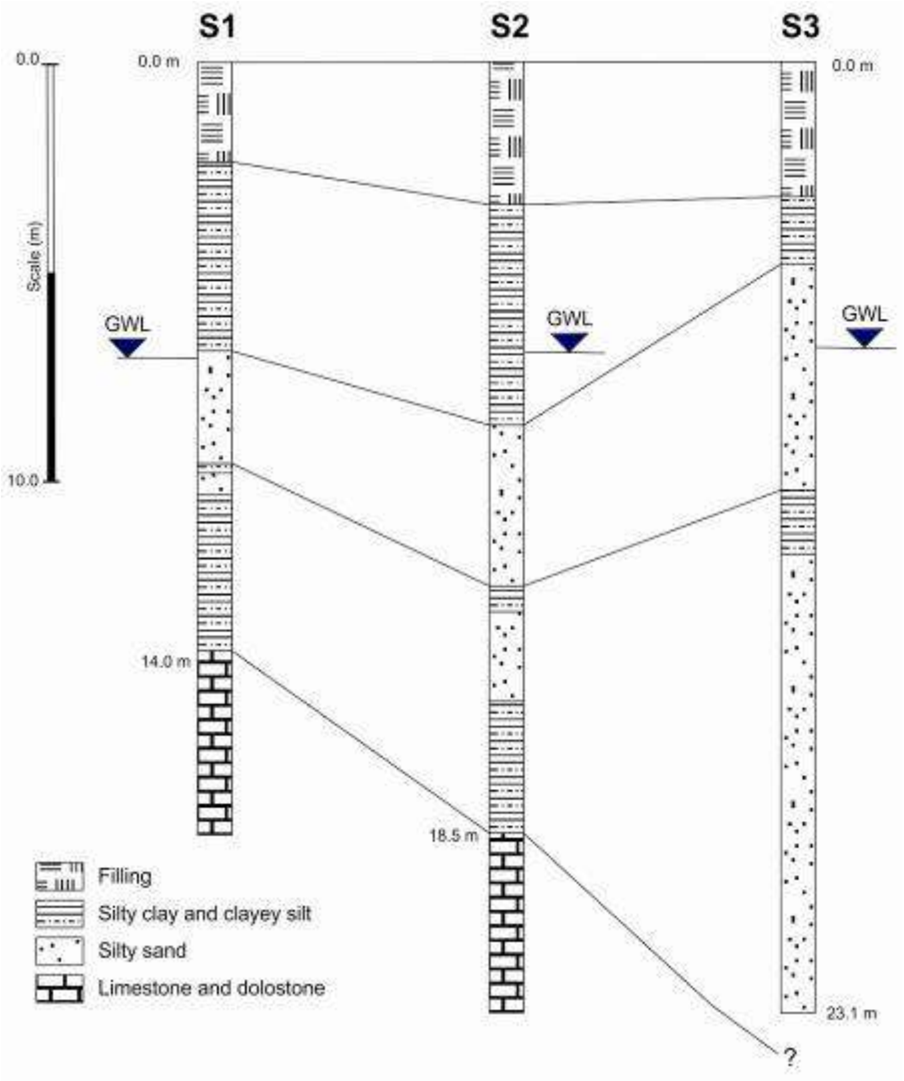

Figure 4. Geotechnical boreholes performed in the Santas Justa and Rufina gothic church. GWL: Ground water level.

Three geotechnical boreholes have been drilled in the proximities of the church (Figure 4) in order to better know the substrate properties and the geometry under the church. Four different lithologies have been recognized (from top to bottom): a) Fillings; b) Silty clays and clayey silts; c) Silty sand; and d) Limestones and dolostones.

The fillings have up to 2 m depth and present a low relative density with standard penetration test results lower than 5 blow counts. Next layer is composed by silty clays and clayey silts that present a slight improvement of the properties (standard penetration test up to 6 blow counts). The penetration values of this lithology increase notably with depth, reaching maximum values up to 15 blow counts on standard penetration test. Silty sands are intercalated among previously described layer. These sands have a higher penetration resistance than fillings and more surficial silty clays layer (11 blow counts). The geotechnical substrate is constituted by carbonatic rocks (Figure 4), limestones and dolostones with refusal values on standard penetration test and uniaxial compressive strength higher than 30 MPa. This layer appears at a depth higher than 16.0 m and is usually used for founding deep foundations due to the considerable improvement of its geotechnical properties. Notice that the depth of this layer changes in a few meters with slopes higher than 0.19 m per meter (>11º) in the church area.

5. Damages description

The Santas Justa and Rufina church has suffered several performances and maintenance works along its history. However, this work is focused on the damages that affected the church during last two decades. Although the more serious damages observed last years have been trigged by deformations induced by regional land subsidence, other kinds of damages (Figure 5) have affected the church: (a) Rock alveolization, (b) Efflorencescences, (c) Biologic activity and (d) Capillary ascent of ground water.

Rock alveolization is observed in sandstones blocks of several elements of the church causing cluster of small cavities and an evident loss of resistance (Figure 5d). These holes can be the result of the stonework (stacking), biological activity (pits) or the action of salt in the irregular porous network of the marble (alveoli) (Chabas and Jeannette, 2001). The salts form efflorescence growing on rock surface (Figure 5c and f) composed of small crystals that can influence both weathering and disintegration (alveolization) of the rocks. Microorganisms (fungi, moho, lichens, etc.) and other organisms (birds, plants, etc.) can cause a wide range of pathologies that are out of the scope of this work. Due to the high water level and the proximity to the Segura River, capillarity ascent affects the lower part of the elements that are in contact with soil although humidity can affect higher elements (cupules, columns heads, etc.) when rain access through preexisting cracks (Figure 5f). Salts from ground water can be transported by capillarity through the rock pore system causing salt crystallization, which is the origin of the previously mentioned efflorescence and alveolization processes.

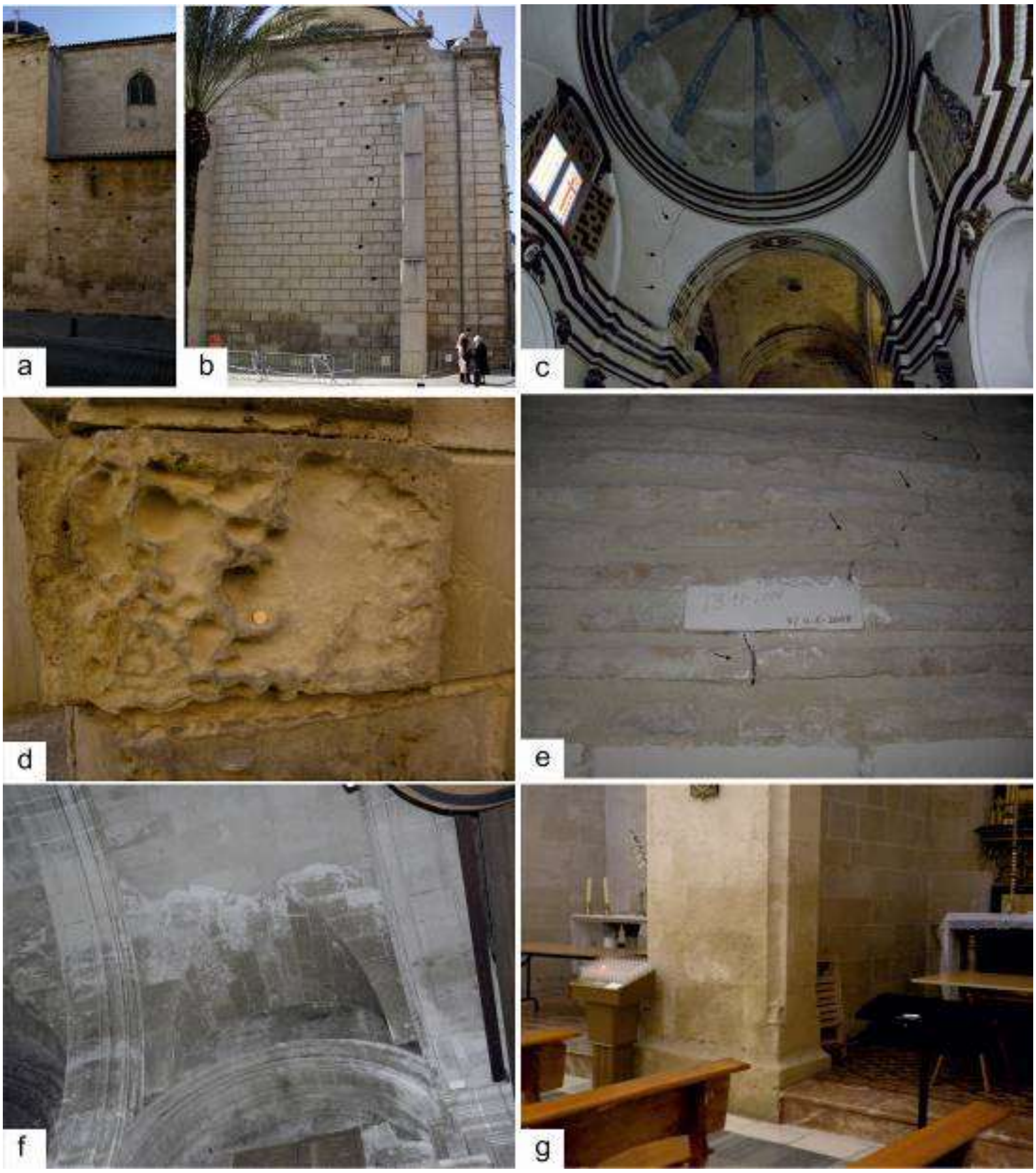

Figure 5. Pathologies observed in the Santas Justa y Rufina church: a) vertical cracks related with a rigidity change; b) cracks due to local effects of counterfort; c) cupola cracks due to differential movements of the base; d) Cluster of small cavities (alveoli); e) masonry cracks induced by differential movements. Notice, the installed plaster markers for crack monitoring f) Efflorescences due to rain infiltration; g) Capillary ascent of water.

Although the above mentioned problems can cause long-term damages, the more dangerous pathologies are affecting structural elements, i.e. walls and columns. Santas Justa and Rufina church is affected by a regional process of subsidence due to water level descend. As is has been previously explained in section 3, accumulated settlements up to 100 mm have been measured in the Orihuela city from 1993 to 2009. The magnitude of these settlements depends on the thickness of the deformable soil, the deformability of the soft soil and the increase of the effective stresses which depends on the piezometric level fall.

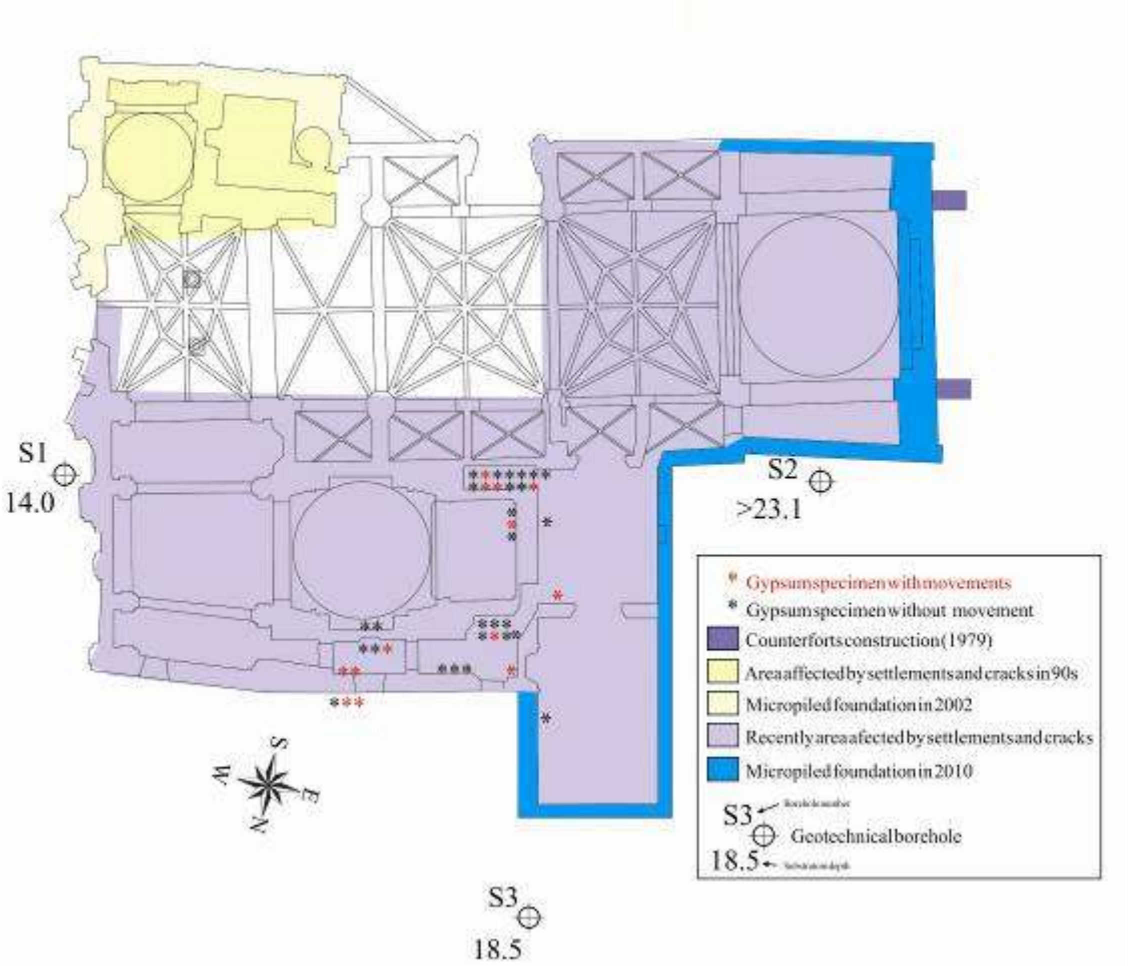

Figure 6. Gypsum plaster markers, geotechnical boreholes location and structural improvement actions performed on the church. Notice that the plaster markers control period was November 2006-June 2008. See geotechnical boreholes lithological description on Figure 4.

The eastern wall that closes the principal chapel suffered an important tilt in 70s decade. The problem was solved by means of the construction of two reinforced concrete counterforts (Figures 5b a 6). After that, deformations affecting the church have occurred in two different phases. In the ninety decade of the last century, important settlements affected the San José chapel zone (Southwest area of the church, Figure 6). Unfortunately no in situ observations are available for this period. As a consequence, the foundation was reinforced in 2002 with micropiles. On a second stage (first decade of present century), deformations affected the whole north zone of the church and the principal chapel area. Ground settlements were visible at the floor of the antesacristy, the sacristy and La Comunión chapel. Multiple cracks where identified in the north, west and east walls, affecting as well La Comunión cupola (Figures 5b, c and e), the sacristy and the antesacristy. Several plaster markers were placed in the cracks in 2006 and controlled in 2008 coinciding with the higher piezometric level fall never known in the Vega Baja of the Segura River basin (Figure 7). Figure 6 shows that multiple cracks grew up for this period as a consequence of the sinking of the walls foundation caused by ground subsidence. This affected zone of the church has been recently repaired in 2010 using micropiles (Figure 6).

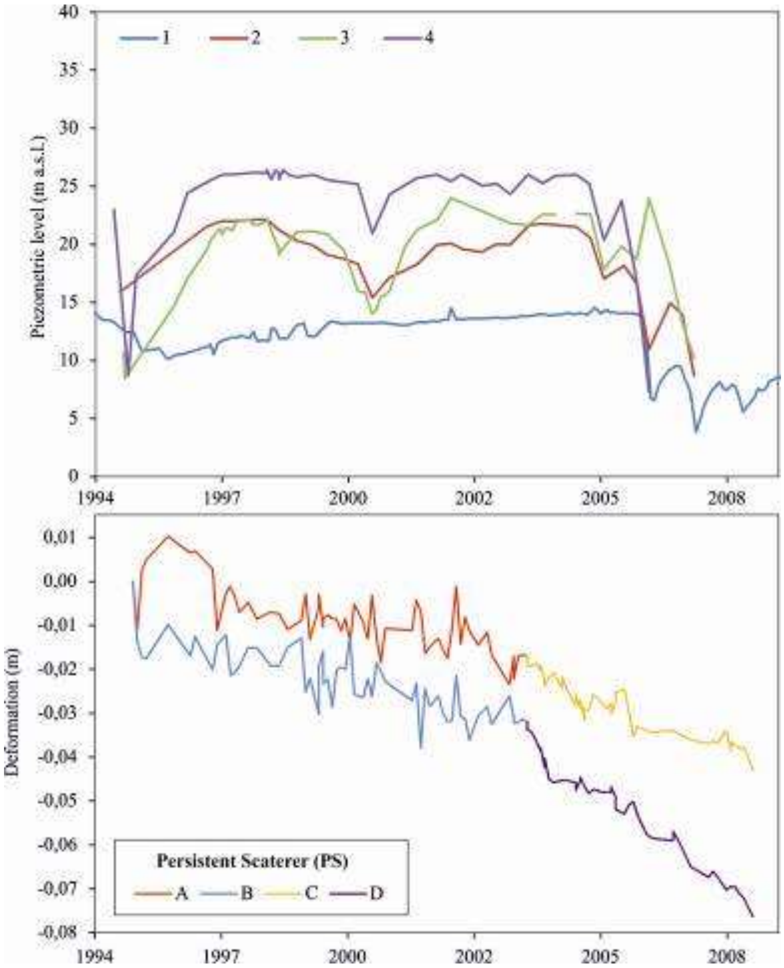

Figure 7. Piezometric level evolution of several piezometers located in the Vega Baja of the Segura river superposed to DInSAR deformation time series of 2 PSs located in the vicinity of the Santas Justa and Rufina church (see A, B, C and D PSs location in Figure 9 and 1, 2, 3 and

4 piezometers location in Figure 3). Notice that PS time series of both DInSAR processed periods has been jointed for neighborhood PSs in order to have complete temporal series for 1995-2008.

6. DInSAR survey

The forensic analysis of the Santas Justa and Rufina church has been supported by DInSAR data. Specifically, in this work ground subsidence measurements have been obtained using a Persistent Scatterer Interferometry (PSI) technique called Stable Point Network (SPN). A in depth description of this technique can be found in Arnaud et al. (2003) and Duro et al. (2005) but a summary is included here for the sake of completeness.

The SPN algorithm uses the DIAPASON (Differential Interferometric Automated Process Applied to Survey Of Nature) interferometric software for all SAR data handling, e.g. co-registration work and interferograms generation. The SPN method generates three main products from a set of Single Look Complex (SLC) SAR images (Duro et al., 2005): (a) the displacement rate (average deformation velocity) measured along line of sight (LOS) of single Persistent Scatterer (PS); (b) a map of height error; and (c) the LOS displacement time series of individual PS (as a function of time).

129 images acquired by the European Space Agency (ESA) ERS-1/2 and Envisat ASAR sensors covering two periods July 1995–December 2005 and January 2004–December 2008 have been used in this work for the deformation study. From all the pairs of images combinations, only interferometric pairs with a perpendicular spatial baseline smaller than 800 m and a temporal baseline shorter than 6 and 3 years for 1995–2005 and 2004–2008 periods respectively, and a relative Doppler centroid difference below 400 Hz have been selected.

The DEM used Digital Elevation Model used for processing has been Shuttle Radar Topography Mission (SRTM) ones. The pixel selection for the estimation of displacements was based on a combination of several quality parameters including low amplitude standard deviation and high model coherence. Coherence is an indicator of the degree of correlation between two SAR images. So, this parameter is used as a measure of the quality of an interferogram. Coherence values near 1 indicate a good correlation although 0 indicates no correlation.

Results of subsidence in the city of Orihuela for both periods (1995-2005 and 2004-2008) are shown in Figure 8. As it can be seen in figure 8a and b, the higher density of PSs corresponds to the urban area of Orihuela. In the Santas Justa y Rufina church neighborhood deformation rates up to -2.1 and -9.5 mm/year for 1995-2005 and 2004-2008 periods respectively have been measured by means of DInSAR (Figure 8a to 8d). Notice that subsidence measured for 2004-2008 period in the vicinity of the church is higher than the measured deformation for the previous period (1995-2005) due to the previously mentioned high piezometric level drop that affected the area because of the aquifer overexploitation. Unfortunately, no PSs are available for both periods for Santas Justa and Rufina church. This is due to the loss of coherence, which is associated to the reforms performed in the cover and façades of the church in 1998 and 2002, just during the period comprised by processing. However, several PSs are available for the nearby areas of the church.

Figure 8g represents N-S cross section of the study area. As it can be noticed, Holocene sediments from the flood plain of the Segura River increase their thickness from the north towards south (from the Sierra de Orihuela relief towards the center of the basin). Subsidence follows a similar trend. The Santas Justa and Rufina church is just located near the Sierra de Orihuela that is composed of carbonatic rocks (dolostones and limestones). This relief deepens under Holocene sediments with high slopes causing important changes in substratum depth as it has been observed in the available boreholes performed in the church perimeter (Figure 4). These substratum changes favor differential settlements occurrence. Differential settlements affecting the church have been computed interpolating the available data for both study periods (Figure 9). The maximum differential settlements have been calculated considering the highest and the lowest subsidence values contained in an area composed by the church and a buffer ring of 14 m providing 12.5 and 24.46 mm for 95-06 and 04-08 periods respectively. The angular distortion has been obtained dividing differential settlement by the distance between the two points that provides the maximum and minimum subsidence value. Computed distortion values for both periods are 1.5×10^{-4} m/m and 3.4×10^{-4} m/m.

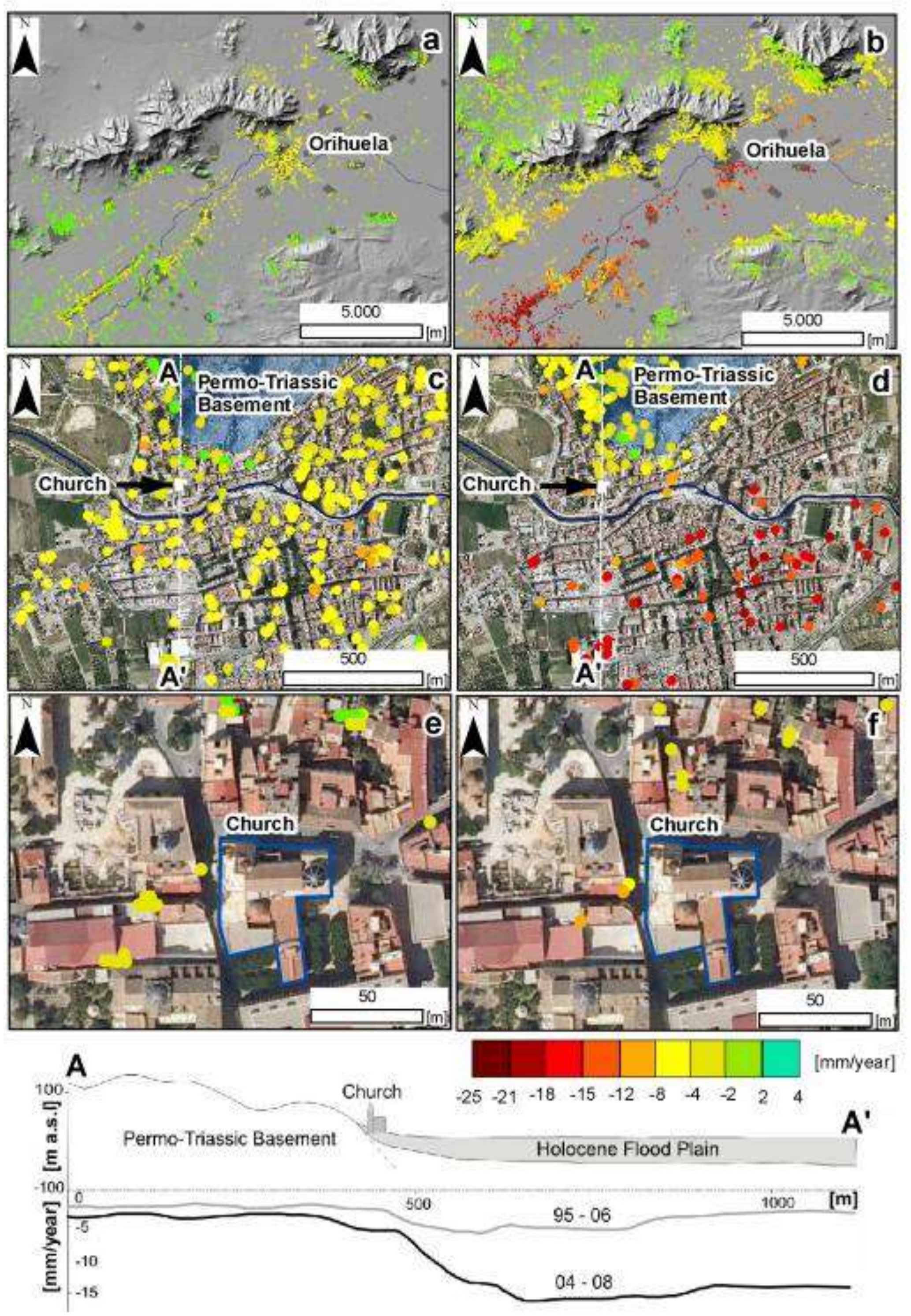

Figure 8. Subsidence measured by means of DInSAR for 1995–2005 and 2004–2008 periods: a) and b) for the whole study area; c) and d) in Orihuela city; e) and f) in the vicinity of the church; g) Geological simplified and subsidence N-S cross section along Orihuela city.

7. Diagnosis

In this section the causes of observed structural pathologies are analysed. Although other pathologies previously described (alveolization, humidity, etc.) affect the Santas Justa and Rufina church, this work is focused on the pathologies caused by ground subsidence.

From a geotechnical point of view, the church is founded over deformable Holocene clays and silts with an intercalated sandy silt layer. All of them present a low bearing capacity with very low values of standard penetration (lower than 15 blow counts). Geotechnical substratum, composed by dolostones and limestones with a high bearing capacity, is placed beneath the previously described layer. The geotechnical substratum depth varies from -14 m in borehole S1 to more than -23.1 m in borehole 2. This means that an important spatial variation of deformable soil thickness is expected in the church subsoil that favours the occurrence of differential settlements of the structure.

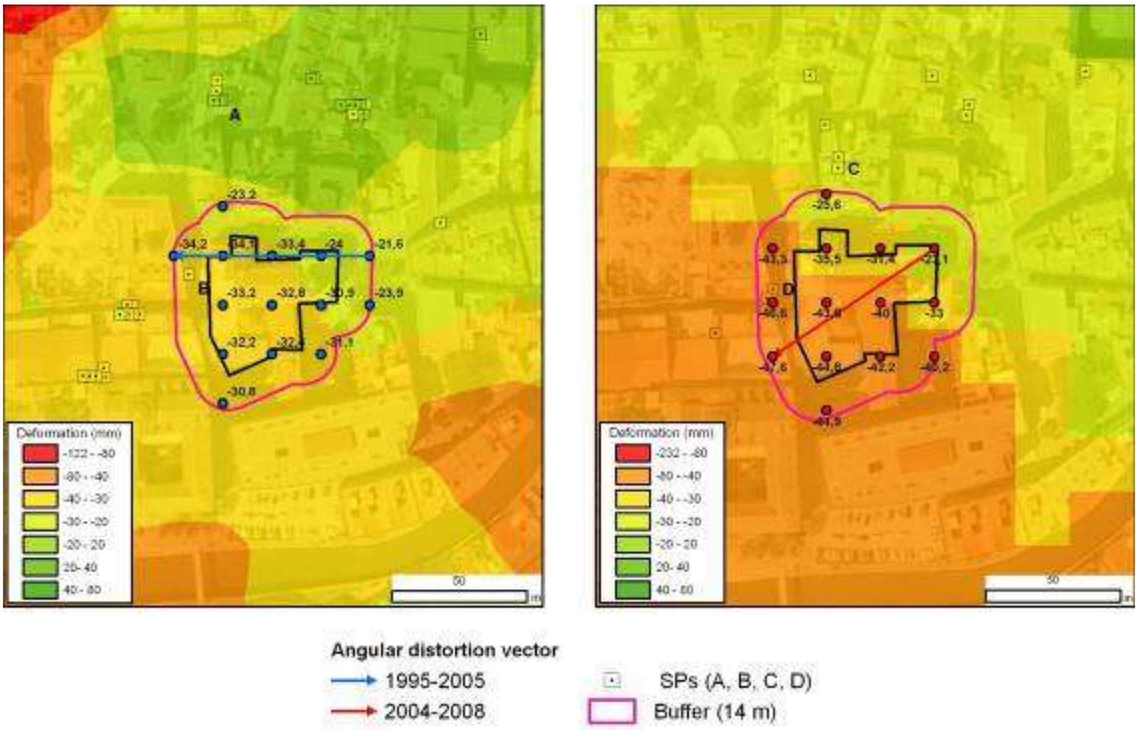

Figure 9. Interpolated DInSAR subsidence in the vicinity of the Santas Justa and Rufina church and computation of differential settlements and maximum deformation gradients for 1995-2006 and 2004-08 periods. Notice that the arrow indicates the direction of maximum deformation gradient.

DInSAR results (Figure 8) show that the whole Orihuela city has suffered subsidence due to water withdrawal at least since 1995 with sinking values up to 100 mm. This subsidence has been proved to be closely related with piezometric level changes (Figure 7) suffering an important acceleration when the piezometric level dropped drastically from 2004 to 2008. Although no PSs are available for the Santas Justa and Rufina church due to the loss of coherence derived from the maintenance works performed in its cover, subsidence rate values up to -21 and -95 mm per year have been measured for 1995-2006 and 2004-2008 periods, respectively, in the nearby areas of the church (Figures 7 and 9). Computed differential settlements using interpolated maps provide maximum differential settlements affecting the church of 12.5 and 24.5 mm for 1995-2006 and 2004-2008 periods, respectively. As it can be notice, these values are lower than the general rule of 25.4 mm (equals to 1”; Terzaghi et al., 1996) of acceptable maximum differential settlement, although during the second period deformations are very close to it. Computed angular distortions reached values of 1.5×10^{-4} m/m and 3.4×10^{-4} m/m that are also lower than the ones generally accepted of (1/1000 m/m).However, the 1995-2008 differential settlement probably got over this value.

The interpolated subsidence values of subsidence also allow interpreting the deformational evolution of the church. As it was explained in section 5, in the ninety decade, high settlements affected the San José chapel zone. Figure 9a shows that the maximum settlements for 1995-2006 period were concentrated on the NW corner of the church, just coinciding with the mentioned area. Also notice that the computed angular distortion (blue arrow) is oriented from E towards W coinciding with the San José chapel zone. The foundation was repaired in 2002 using micropiles. More recent damages are concentrated in the SE zones (La Comunión chapel, antesacristy and sacristy; Figures 6). As it was explained in section 5 field work has been performed in order to identify the damages affecting this area. Observed damages consist principally on floor settlements (pavement irregularities are easily recognized) and wall cracks that can affect other elements. Figure 9b shows that maximum interpolated settlements for the 2004-2008 period are concentrated on the SW corner of the church with a maximum angular distortion direction NE-SW (the church has undergone a tilt towards the SW) in agreement with field observations.

8. Conclusions

The gothic church of Santas Justa and Rufina, located in Orihuela (SE, Spain) has suffered several damages due to regional subsidence processes, scarcely related with piezometric level oscillations. The church subsoil is favourable for subsidence occurrence. It is composed of fillings and Holocene fine materials (silts and clays) with some coarse intercalations (silty sand) that reach thickness higher than 23.1 m at the E of the church. Field works have allowed to identify the more affected zones of the church providing detailed data about the kinds of pathologies affecting the church. Moreover, DInSAR data have permitted to perform a global interpretation of the deformations affecting the church. Although, no PS are available for the church due to the loss of interferometric coherence caused by the maintenance works performed in the church cover, settlement values up to -9.5 mm/year for 2004-2008 have been measured by means of DInSAR in the vicinity of the church. Furthermore, the analysis of the interpolated DInSAR data has allowed estimating differential settlements of 24.5 mm and angular distortions of 3.4 x 10^{-4} m/m for the 2004-2008 periods affecting the church. Although the computed values of differential settlements for both independent periods are lower than allowable settlement (<25.4 mm equals to 1") probably, the values corresponding to the whole subsidence temporal period (1995-2008) exceed this tolerable settlement. These data are consistent with in situ data and field observations proving that DInSAR is a powerful tool that can be very useful for performing buildings forensic analysis jointly with in situ data.

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