

This paper has to be cited as: *Tomás, R., García-Barba, J., Cano, M., Sanabria, M.P., Ivorra, S., Duro, J. & Herrera, G. 2012. Subsidence damage assessment of a gothic church using Differential Interferometry and field data. Structural Health Monitoring, 11, 751-762.* The final publication is available at SAGE journals via: <http://shm.sagepub.com/content/11/6/751.abstract>

---

# 1           **Subsidence damage assessment of a gothic church using** 2                           **Differential Interferometry and field data**

3           R. Tomás<sup>1</sup>, J. García-Barba<sup>1</sup>, M. Cano<sup>1</sup>, S. Ivorra<sup>1</sup>, M.P. Sanabria<sup>2</sup>, J. Duro<sup>3</sup>, G. Herrera<sup>2</sup>

4           (1) *Departamento de Ingeniería de la Construcción, Obras Públicas e Infraestructuras*  
5                 *Urbanas. Escuela Politécnica Superior, Universidad de Alicante, P.O. Box 99, E-03080*  
6                 *Alicante, Spain. E-mail: [roberto.tomas@ua.es](mailto:roberto.tomas@ua.es)*

7           (2) *Instituto Geológico y Minero de España, Ríos Rosas 23, E-28003 Madrid, Spain. E-*  
8                 *mail: [g.herrera@igme.es](mailto:g.herrera@igme.es)*

9           (3) *Altamira Information, c/ Còrsega, 381-387, 2n 3a - E-08037 Barcelona, Spain. E-mail:*  
10                 *[javier.duro@altamira-information.com](mailto:javier.duro@altamira-information.com)*

## 11 12    **Abstract**

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

26  
27    **Keywords:** Forensic analysis, DInSAR, ground subsidence, gothic church, historic building  
28    monitoring

29  
30    **Research highlights:** Santas Justa and Rufina has suffered several kinds of pathologies along  
31    its history > The last two decades the church has been affected by ground subsidence  
32    processes due to aquifer overexploitation > Subsidence has seriously affected the church > The  
33    joint use of DInSAR techniques and field observations has permitted to better understand  
34    subsidence pathologic processes affecting the church

## 35 1. Introduction

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

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

68

## 69 2. Description of the gothic church

70 The Santas Justa and Rufina church, declared a Spanish National Monument in 1971, is  
71 located in Orihuela (Alicante province, Spain)(Figure 1). It is a Catholic church built in the XIV  
72 century and reformed in the XVI and XVIII centuries, presenting both Gothic and Baroque

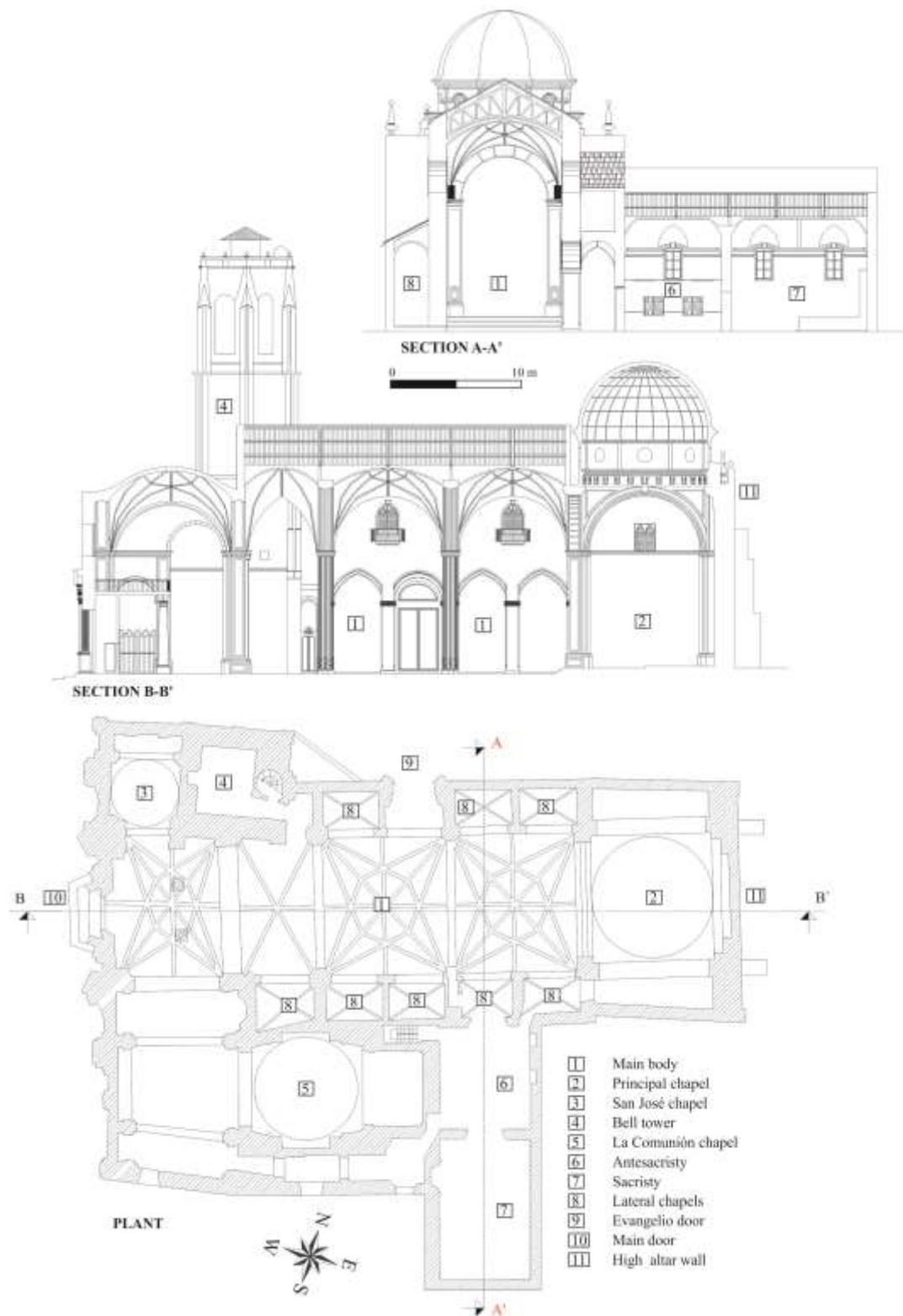
73 influences. It consists of a main body with lateral chapels located between the counterforts  
74 (Figures 1b and 2). Among all lateral chapels there are two higher chapels, San José chapel,  
75 located at the NW of the church, and La Comunción chapel, placed at the SW. There are two  
76 doors, the main located at the west façade (Figures 1a and 2), and a lateral door (Evangelio  
77 door) placed at north façade (Figures 1c and 2). The sacristy, with a square plant, and the  
78 antesacristy, with a rectangular plant, are sited at the SE part of the church. Finally, the bell  
79 tower found at the north of the church reaches a height of 35.5 m (Figure 1a). The entire  
80 building is built of masonry with bricks and ashlar and is directly founded over silts and clays  
81 overlaying the church that will be described in detail on section 4.

82 .



83 .

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



87

88

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

89

### 90 **3. Available information and previous works**

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

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

112

### 113 **4. Geological and geotechnical characterization**

#### 114 **4.1. Geological setting**

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

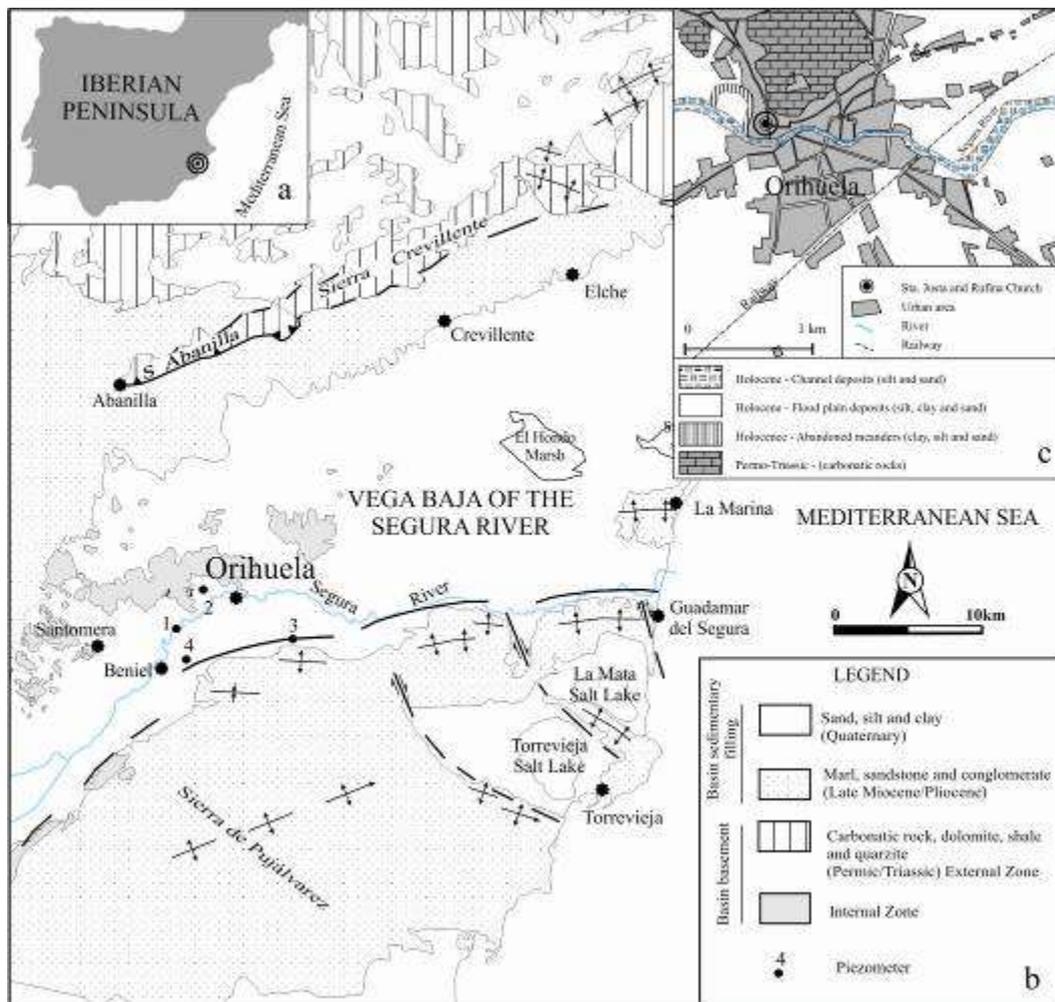
120 The Mesozoic basement of the basin consists of carbonate and evaporitic rocks from the Betic  
121 External Zones protrude at the N and E area of the study zone (Delgado et al, 2002). The Bajo  
122 Segura Basin is filled by Neogene–Quaternary sediments (Figure 3).

123 The valley filling is composed on Holocene sediments at the ground surface beyond Pleistocene  
124 sediments deposited by River Segura depositional activity, whereas the eastern zones towards

125 the Mediterranean Sea are occupied by littoral and lagoonal sediments (Delgado et al., 2002).  
 126 Anthropogenic deposits can be also found at certain points in the valley generally related with urban  
 127 areas. Recent sediments are the most compressible ones in the area and the most problematic  
 128 from a geotechnical point of view.

129 The study area belongs to the so-called "Guadalentín–Segura Quaternary aquifer System N°  
 130 47" (IGME, 1986), an aquifer characterized by two units: a) a surface unconfined aquifer unit  
 131 with a low conductivity composed by fine sand and silts deposited by the recent activity of the  
 132 Segura River and coastal processes (towards the E of the zone) whose water table is found a  
 133 few meters below the ground surface. b) A second unit formed by gravels, usually interbedded  
 134 with marls that constitutes a confined aquifer with greater hydraulic conductivity than the  
 135 superficial aquifer (DPA-ITGE, 1996). The upper aquifer is the most scarcely exploited.

136



137

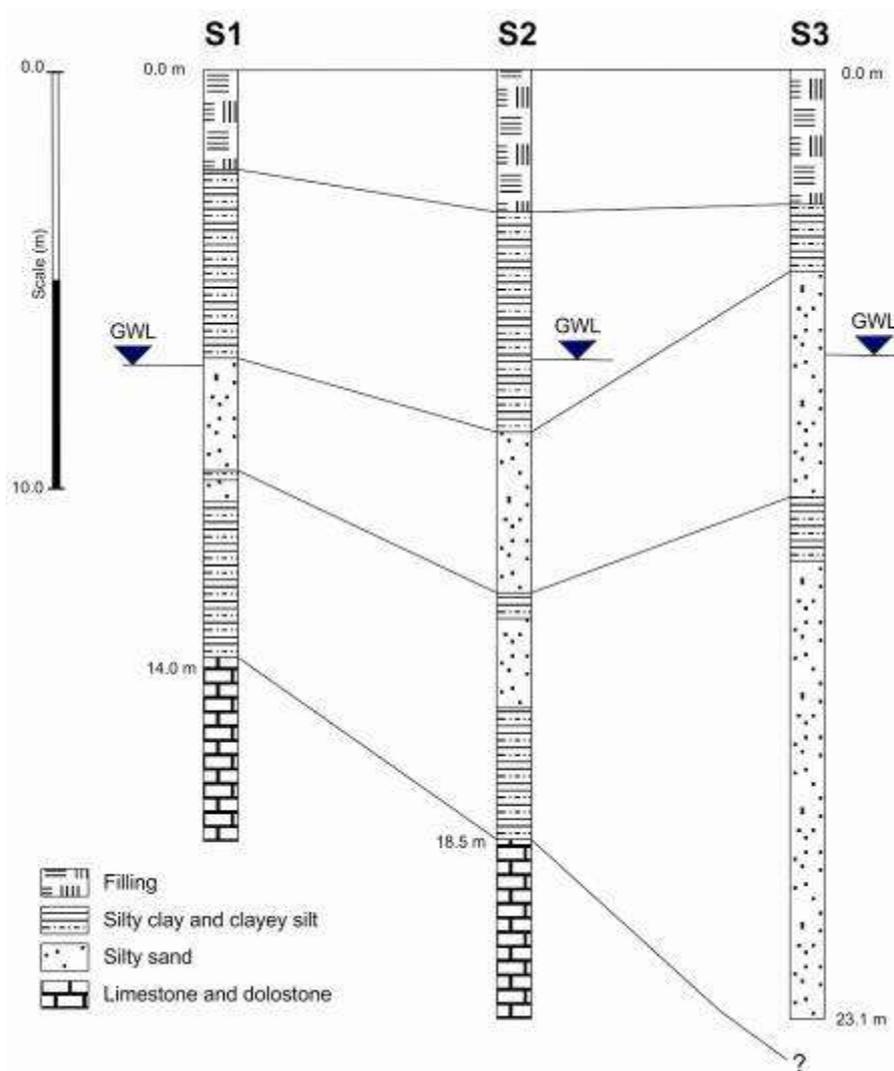
138 Figure 3. Location and geological setting of the city of Orihuela and the Santa Justa and Rufina  
 139 Church.

140

141 **4.2. Geotechnical setting**

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

151



152

153 Figure 4. Geotechnical boreholes performed in the Santos Justa and Rufina gothic church.

154

GWL: Ground water level.

155

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

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

172

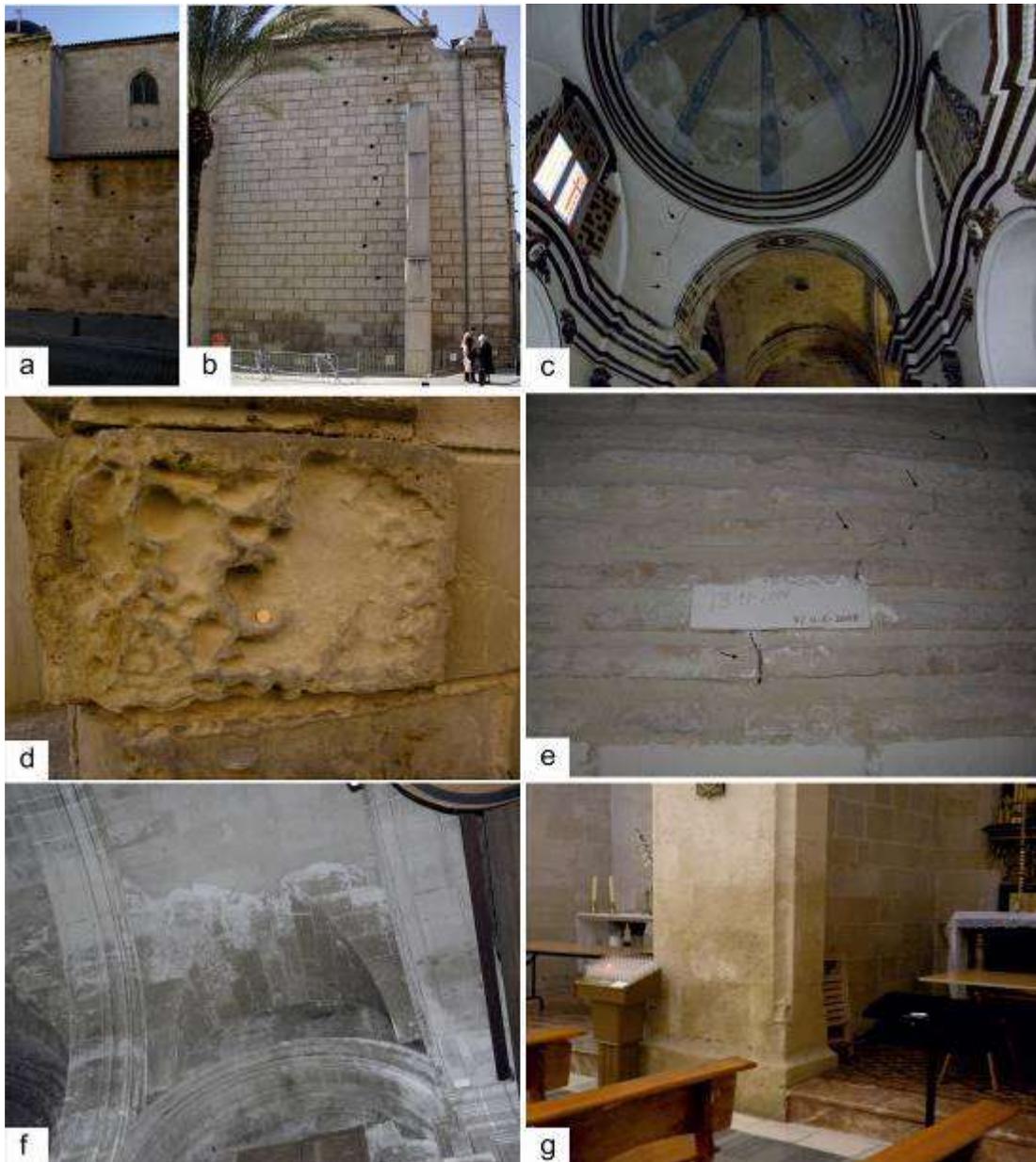
### 173 **5. Damages description**

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

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

191 capillarity through the rock pore system causing salt crystallization, which is the origin of the  
192 previously mentioned efflorescence and alveolization processes.

193

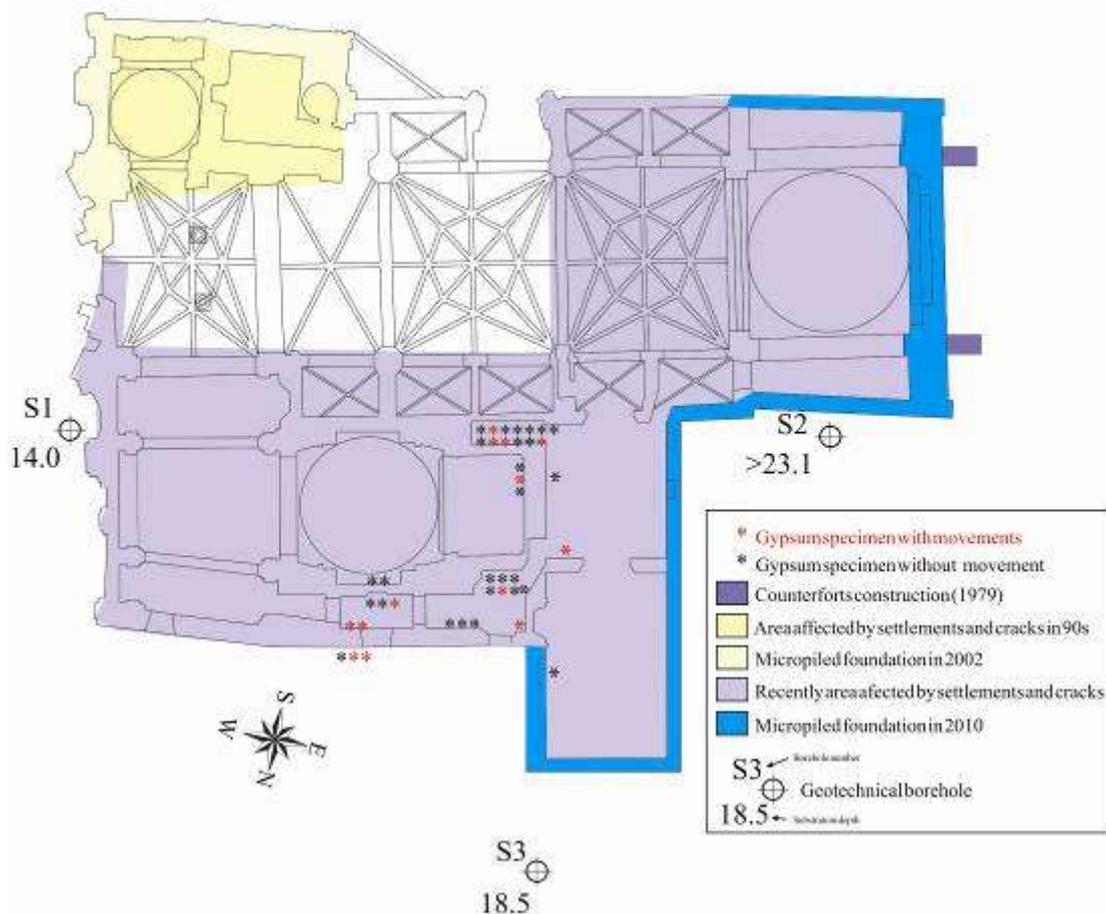


194

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

200

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



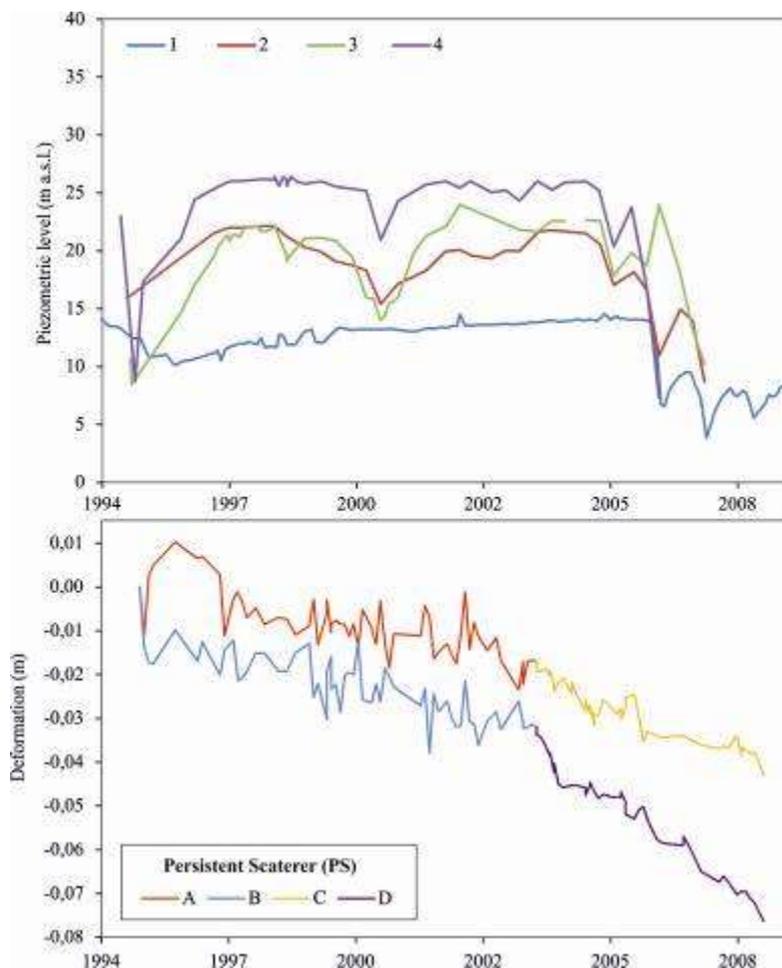
208  
209 Figure 6. Gypsum plaster markers, geotechnical boreholes location and structural improvement  
210 actions performed on the church. Notice that the plaster markers control period was November  
211 2006-June 2008. See geotechnical boreholes lithological description on Figure 4.

212  
213 The eastern wall that closes the principal chapel suffered an important tilt in 70s decade. The  
214 problem was solved by means of the construction of two reinforced concrete counterforts  
215 (Figures 5b a 6). After that, deformations affecting the church have occurred in two different  
216 phases. In the ninety decade of the last century, important settlements affected the San José  
217 chapel zone (Southwest area of the church, Figure 6). Unfortunately no in situ observations are

218 available for this period. As a consequence, the foundation was reinforced in 2002 with  
219 micropiles. On a second stage (first decade of present century), deformations affected the  
220 whole north zone of the church and the principal chapel area. Ground settlements were visible  
221 at the floor of the antesacristy, the sacristy and La Comunción chapel. Multiple cracks where  
222 identified in the north, west and east walls, affecting as well La Comunción cupola (Figures 5b, c  
223 and e), the sacristy and the antesacristy. Several plaster markers were placed in the cracks in  
224 2006 and controlled in 2008 coinciding with the higher piezometric level fall never known in the  
225 Vega Baja of the Segura River basin (Figure 7). Figure 6 shows that multiple cracks grew up for  
226 this period as a consequence of the sinking of the walls foundation caused by ground  
227 subsidence. This affected zone of the church has been recently repaired in 2010 using  
228 micropiles (Figure 6).

229

230



231

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

235 4 piezometers location in Figure 3). Notice that PS time series of both DInSAR processed  
236 periods has been jointed for neighborhood PSs in order to have complete temporal series for  
237 1995-2008.

238

## 239 **6. DInSAR survey**

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

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

252 129 images acquired by the European Space Agency (ESA) ERS-1/2 and Envisat ASAR  
253 sensors covering two periods July 1995–December 2005 and January 2004–December 2008  
254 have been used in this work for the deformation study. From all the pairs of images  
255 combinations, only interferometric pairs with a perpendicular spatial baseline smaller than 800  
256 m and a temporal baseline shorter than 6 and 3 years for 1995–2005 and 2004–2008 periods  
257 respectively, and a relative Doppler centroid difference below 400 Hz have been selected.

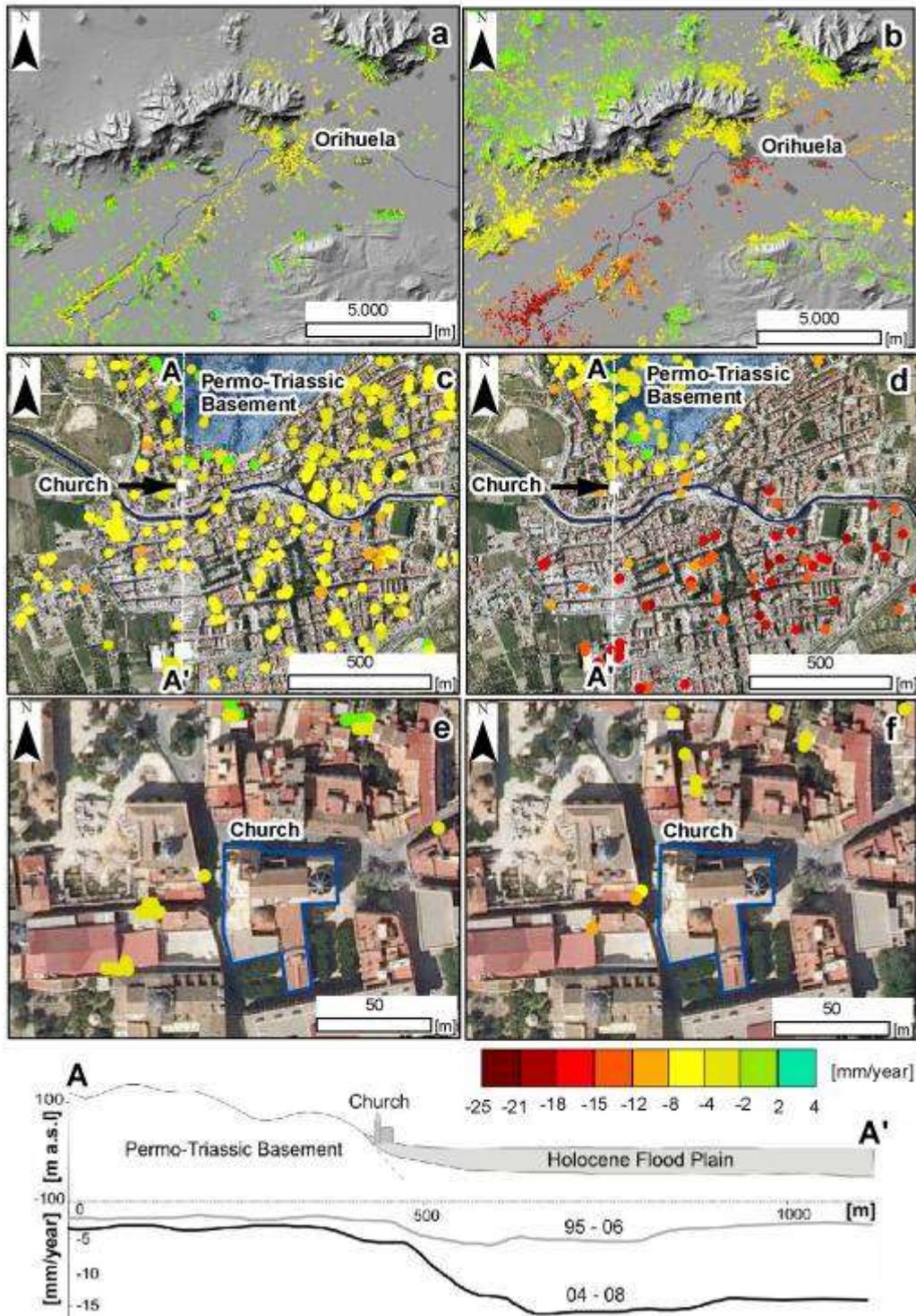
258 The DEM used Digital Elevation Model used for processing has been Shuttle Radar  
259 Topography Mission (SRTM) ones. The pixel selection for the estimation of displacements was  
260 based on a combination of several quality parameters including low amplitude standard  
261 deviation and high model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

265 Results of subsidence in the city of Orihuela for both periods (1995-2005 and 2004-2008) are  
266 shown in Figure 8. As it can be seen in figure 8a and b, the higher density of PSs corresponds  
267 to the urban area of Orihuela. In the Santas Justa y Rufina church neighborhood deformation  
268 rates up to -2.1 and -9.5 mm/year for 1995-2005 and 2004-2008 periods respectively have been  
269 measured by means of DInSAR (Figure 8a to 8d). Notice that subsidence measured for 2004-  
270 2008 period in the vicinity of the church is higher than the measured deformation for the

271 previous period (1995-2005) due to the previously mentioned high piezometric level drop that  
272 affected the area because of the aquifer overexploitation. Unfortunately, no PSs are available  
273 for both periods for Santas Justa and Rufina church. This is due to the loss of coherence, which  
274 is associated to the reforms performed in the cover and façades of the church in 1998 and  
275 2002, just during the period comprised by processing. However, several PSs are available for  
276 the nearby areas of the church.

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

292



293

294 Figure 8. Subsidence measured by means of DInSAR for 1995–2005 and 2004–2008 periods:

295 a) and b) for the whole study area; c) and d) in Orihuela city; e) and f) in the vicinity of the

296 church; g) Geological simplified and subsidence N-S cross section along Orihuela city.

297

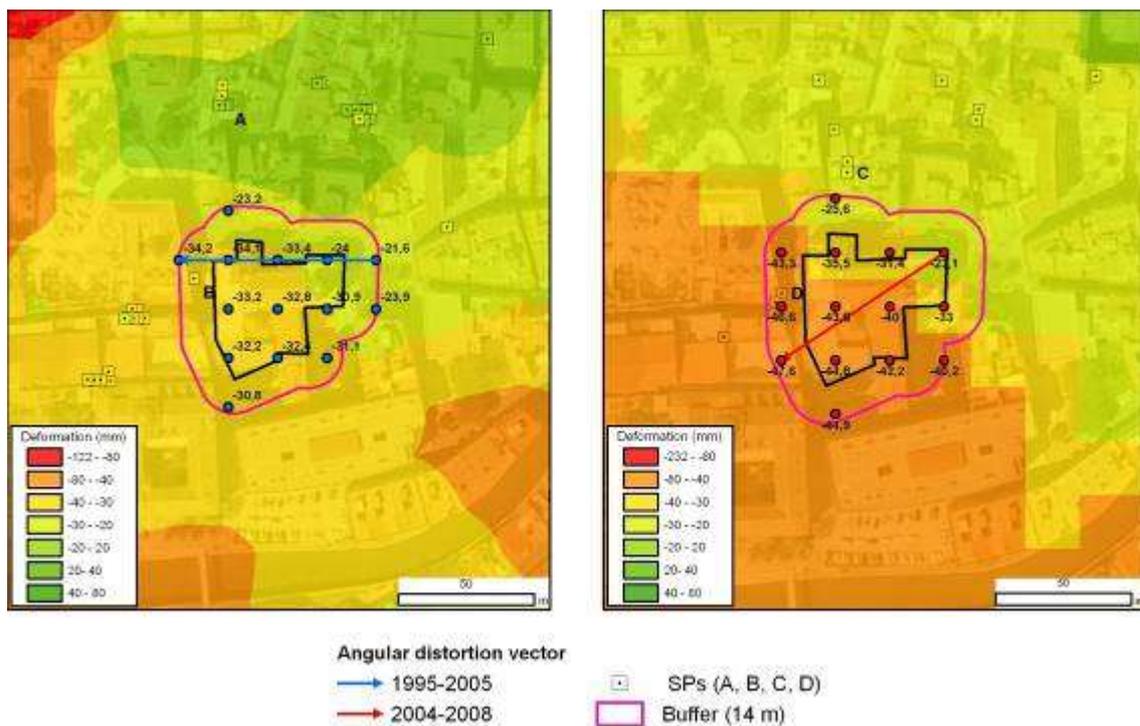
298

299 **7. Diagnosis**

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

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

311



312

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

317

318 DInSAR results (Figure 8) show that the whole Orihuela city has suffered subsidence due to  
319 water withdrawal at least since 1995 with sinking values up to 100 mm. This subsidence has

320 been proved to be closely related with piezometric level changes (Figure 7) suffering an  
321 important acceleration when the piezometric level dropped drastically from 2004 to 2008.  
322 Although no PSs are available for the Santas Justa and Rufina church due to the loss of  
323 coherence derived from the maintenance works performed in its cover, subsidence rate values  
324 up to -21 and -95 mm per year have been measured for 1995-2006 and 2004-2008 periods,  
325 respectively, in the nearby areas of the church (Figures 7 and 9). Computed differential  
326 settlements using interpolated maps provide maximum differential settlements affecting the  
327 church of 12.5 and 24.5 mm for 1995-2006 and 2004-2008 periods, respectively. As it can be  
328 notice, these values are lower than the general rule of 25.4 mm (equals to 1"; Terzaghi et al.,  
329 1996) of acceptable maximum differential settlement, although during the second period  
330 deformations are very close to it. Computed angular distortions reached values of  $1.5 \times 10^{-4}$   
331 m/m and  $3.4 \times 10^{-4}$  m/m that are also lower than the ones generally accepted of (1/1000  
332 m/m). However, the 1995-2008 differential settlement probably got over this value.

333 The interpolated subsidence values of subsidence also allow interpreting the deformational  
334 evolution of the church. As it was explained in section 5, in the ninety decade, high settlements  
335 affected the San José chapel zone. Figure 9a shows that the maximum settlements for 1995-  
336 2006 period were concentrated on the NW corner of the church, just coinciding with the  
337 mentioned area. Also notice that the computed angular distortion (blue arrow) is oriented from E  
338 towards W coinciding with the San José chapel zone. The foundation was repaired in 2002  
339 using micropiles. More recent damages are concentrated in the SE zones (La Comunción  
340 chapel, antesacristy and sacristy; Figures 6). As it was explained in section 5 field work has  
341 been performed in order to identify the damages affecting this area. Observed damages consist  
342 principally on floor settlements (pavement irregularities are easily recognized) and wall cracks  
343 that can affect other elements. Figure 9b shows that maximum interpolated settlements for the  
344 2004-2008 period are concentrated on the SW corner of the church with a maximum angular  
345 distortion direction NE-SW (the church has undergone a tilt towards the SW) in agreement with  
346 field observations.

347

## 348 **8. Conclusions**

349 The gothic church of Santas Justa and Rufina, located in Orihuela (SE, Spain) has suffered  
350 several damages due to regional subsidence processes, scarcely related with piezometric level  
351 oscillations. The church subsoil is favourable for subsidence occurrence. It is composed of  
352 fillings and Holocene fine materials (silts and clays) with some coarse intercalations (silty sand)  
353 that reach thickness higher than 23.1 m at the E of the church. Field works have allowed to  
354 identify the more affected zones of the church providing detailed data about the kinds of  
355 pathologies affecting the church. Moreover, DInSAR data have permitted to perform a global  
356 interpretation of the deformations affecting the church. Although, no PS are available for the  
357 church due to the loss of interferometric coherence caused by the maintenance works

358 performed in the church cover, settlement values up to -9.5 mm/year for 2004-2008 have been  
359 measured by means of DInSAR in the vicinity of the church. Furthermore, the analysis of the  
360 interpolated DInSAR data has allowed estimating differential settlements of 24.5 mm and  
361 angular distortions of  $3.4 \times 10^{-4}$  m/m for the 2004-2008 periods affecting the church. Although  
362 the computed values of differential settlements for both independent periods are lower than  
363 allowable settlement (<25.4 mm equals to 1") probably, the values corresponding to the whole  
364 subsidence temporal period (1995-2008) exceed this tolerable settlement. These data are  
365 consistent with in situ data and field observations proving that DInSAR is a powerful tool that  
366 can be very useful for performing buildings forensic analysis jointly with in situ data.

367

### 368 **Acknowledgements**

369 Authors José Luis Satorre (Priest of Santa Justa and Rufina church), Excelentísimo  
370 Ayuntamiento de Orihuela and Jenaro Vera (University of Alicante) by the provided information  
371 and/or their useful comments. The European Space Agency (ESA) TerraFirma project has  
372 funded all the SAR data processing with the SPN technique. Additionally, this work has been  
373 partially financed by supported by the projects: TEC-2008-06764, ACOMP/2010/082, VIGROB-  
374 157, 15224/PI/10 and BEST-2011/225.

375

### 376 **References**

377 Batuhan Osmanoğlu, Timothy H. Dixon, Shimon Wdowinski, Enrique Cabral-Cano and Yan  
378 Jiang (2010). Mexico City subsidence observed with persistent scatterer InSAR. *International*  
379 *Journal of Applied Earth Observation and Geoinformation* 13, 1-12

380 Bénédicte Fruneau, Benoît Deffontaines, Jean-Paul Rudant, Anne-Marie Le Parmentier (2005).  
381 Monitoring vertical deformation due to water pumping in the city of Paris (France) with  
382 differential interferometry Original Research Article *Comptes Rendus Geosciences*, Volume  
383 337, Issue 13, September-October 2005, Pages 1173-1183

384 Bru, G., Herrera, G., Tomás, R., Duro, J., De la Vega, R., Mulas, J. Control of deformation of  
385 buildings affected by subsidence using persistent scatterer interferometry. *Structure and*  
386 *infrastructure engineering*. Accepted in press, DOI: 10.1080/15732479.2010.519710, 2010.

387 Chabas, A., Jeannette, D. (2001). Weathering of marbles and granites in marine environment:  
388 petrophysical properties and special role of atmospheric salts *Environmental Geology* 40, 359-  
389 368.

390 De Larouzière, F.D., Bolze, J., Bordet, P., Hernández, J., Montenat, C., Ott D'Estevou, P.  
391 (1988). The Betic segment of the lithospheric trans-Alboran shear zone during the Late  
392 Miocene. *Tectonophysics* 152, 41-52.

- 393 Delgado J, Alfaro P, Andréu JM, Cuenca A, Doménech C, Estévez A, Soria JM, Tomás R,  
394 Yébenes A. (2003). Engineering-geological model of the Segura river flood plain (SE Spain): a  
395 case study for engineering planning. *Eng. Geol.*, 68, 171-187.
- 396 Herrera, G., Tomas, R., Monells, D., Centolanza, G., Mallorqui, J.J., Vicente, F., Navarro, V.D.,  
397 Lopez-Sanchez, J.M, Cano, M., Mulas, J., Sanabria, M. (2010). Analysis of subsidence using  
398 TerraSAR-X data: Murcia case study. *Engineering Geology*, 116, 284-295, 2010
- 399 Ivorra, S., F.J. Pallarés, J.M. Adams, R. Tomás. An evaluation of the incidence of soil  
400 subsidence on the dynamic behaviour of a Gothic bell tower. *Engineering Structures*. 32, 8,  
401 2318-2325, 2010.
- 402 Sandra I.N. Heleno, Luís G.S. Oliveira, Maria J. Henriques, Ana P. Falcão, José N.P. Lima,  
403 Geraint Cooksley, Alessandro Ferretti, Ana M. Fonseca, João P. Lobo-Ferreira, João F.B.D.  
404 Fonseca (2011). Persistent Scatterers Interferometry detects and measures ground subsidence  
405 in Lisbon. *Remote Sensing of Environment*, Volume 115, Issue 8, 15 August 2011, Pages 2152-  
406 2167.
- 407 Sanz de Galdeano, C. (1990). Geologic evolution of the Betic Cordilleras in Western  
408 Mediterranean, Mio-cene to the present. *Tectonophysics* 172, 107-119.
- 409 Stramondo, S., F. Bozzano, F. Marra, U. Wegmuller, F.R. Cinti, M. Moro, M. Saroli (2008).  
410 Subsidence induced by urbanisation in the city of Rome detected by advanced InSAR technique  
411 and geotechnical investigations. *Remote Sensing of Environment*, Volume 112, Issue 6, 16  
412 June 2008, Pages 3160-3172
- 413 Terzaghi, K., Peck, R.B., Mesri, G. (1996). *Soil mechanics in engineering practice*. 3<sup>rd</sup> edition.  
414 John Wiley & Sons, 592 pp.
- 415 Tomás, R., Herrera, G., Lopez-Sanchez, J.M., Vicente, F., Cuenca, A. & Mallorquí, J.J. (2010).  
416 Study of the land subsidence in the Orihuela city (SE Spain) using PSI data: distribution,  
417 evolution and correlation with conditioning and triggering factors. *Engineering Geology*, 115,  
418 105-121.
- 419 Tomás, R., Lopez-Sanchez, J.M., Delgado, J., Mallorquí, J.J. & Herrera, G. (2008). DInSAR  
420 monitoring of aquifer compaction due to water withdrawal: Vega Baja and Media of the Segura  
421 river (SE, Spain) case study. In J.M. Sánchez (Ed.), *Drought: causes, effects and predictions*  
422 (pp. 253-276). New York: NOVA Publishers.
- 423 Tomás, R., Lopez-Sanchez, J.M., Delgado, J., Vicente, F., Cuenca, A., Mallorquí, J.J., Blanco,  
424 P. & Duque S. (2007). DInSAR monitoring of land subsidence in Orihuela city, Spain:  
425 comparison with geotechnical data. *IEEE Int. Geosci. Remote Sens. Symp., IGARSS 2007*,  
426 Barcelona, 23-28 Julio, 3027-3030.