Case Report

A-DInSAR Monitoring of Landslide and Subsidence Activity: A Case of Urban Damage in Arcos de la Frontera, Spain

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Abstract: Terrain surface displacements at a site can be induced by more than one geological process. In this work, we use advanced differential interferometry SAR (A-DInSAR) to measure ground deformation in Arcos de la Frontera (SW Spain), where severe damages related to landslide activity and subsidence have occurred in recent years. The damages are concentrated in two residential neighborhoods constructed between 2001 and 2006. One of the neighborhoods, called La Verbena, is located at the head of an active retrogressive landslide that has an extension of around 0.17×10^6 m^2 and developed in weathered clayey soils. Landslide motion has caused building deterioration since they were constructed. After a heavy rainfall period in winter 2009–2010, the movement was accelerated, worsening the situation. The other neighborhood, Pueblos Blancos, was built over a poorly compacted artificial filling undergoing a spatially variable consolidation process which has also led to severe damage to buildings. For both cases, a short set of C-band data from the "ENVISAT 2010+" project has been used to monitor surface displacement for the period spanning April 2011–January 2012. In this work we characterize the mechanism of both ground deformation processes using in situ and remote sensing techniques along with a detailed geological interpretation and urban damage distribution.

Keywords: slow-moving landslides; subsidence; urban damage; "ENVISAT 2010+" project

1. Introduction

In the past years, the use of multi-temporal differential SAR interferomery (DInSAR) has proven to be a very useful tool to monitor slow moving landslides [1–9] and subsidence [10–16]. These two processes are widespread geological hazards characterized by motion rates reaching several cm/year, that can cause different degrees of structural damage to buildings and infrastructure. Landslide is a general term that describes the downslope movement of a mass of rock or soil [17,18]. Slope failures can even occur with low inclination angles, as failure not only depends on the effects of gravity, but on

a variety of factors such as the geotechnical behavior of the materials (determined by its composition and microstructure), discontinuities, water and external loads. Subsidence is the vertical downward movement of the ground surface with not much or no horizontal motion [19] that can be due to soil consolidation, among other phenomena. If the compaction is spatially uneven, the structures at the surface will undergo differential settlement. The high spatial density of measure points provided by DInSAR allows the study of urban damage caused simultaneously by ground surface displacements related to different natural processes [20,21].

Even though high spatial resolution sensors, i.e., TerraSAR-X or CosmoSkyMed, are the most adequate for studying urban areas [22–24], the Synthetic Aperture Radar (SAR) images are acquired under request, and thus no images might be available to study past events. On the other hand, several works have demonstrated the usefulness of C-band SAR images acquired by medium spatial resolution sensors such as ERS and ENVISAT satellites to monitor urban structures [22,25–28]. They provide a free continuous archive of SAR images from 1992 to 2012 with high spatial coverage, which continues with the Sentinel-1 satellites launched in April 2014. In October 2010 the orbit of the ENVISAT satellite was lowered from about 800 km to about 783 km ("ENVISAT 2010+" project) in order to conserve fuel and extend its life until April 2012.

Arcos de la Frontera is a monumental town located in the province of Cádiz (Andalusia, Spain, Section 2.1) that has gone through a vast urban expansion in the past years. Two neighborhoods located in new residential areas, La Verbena (LV) and Pueblos Blancos (PB), have been affected by severe damage related to different ground motion processes, a retrogressive active landslide and the uneven compaction of a loose artificial earth fill, respectively. Urban damage related to the landslide activity has been occurring for decades. The unstable slope is constituted by weathered clayey soil of the Guadalquivir Blue Marls (GBM) geological formation, which is extensively present in the region and typically undergoes serious geotechnical problems. In recent years, landslide motion has been progressively deteriorating La Verbena buildings, which were constructed in 2004. In October 2009, one of the buildings that housed 22 families was evacuated as the tilt of one part with respect to the other had led to severe structural damage. Shortly after, an intense precipitation period during December 2009 to March 2010 aggravated the situation; the entire building was declared derelict and nearby buildings, public spaces and water supplies were affected. Remediation efforts are still being carried out in order to stabilize the landslide. Building pathologies in Pueblos Blancos began shortly after construction in 2006 and are related to differential settlements that the structures are not capable of absorbing. Although engineering remedial works were performed, ground movement and building deterioration continued afterwards.

The aim of this paper is, firstly, to perform a detailed characterization of the geological processes involved in two damaged urban areas in Arcos de la Frontera; later, to carry out a thorough damage inventory in buildings and surrounding areas; and, finally, to correlate them with measured surface displacements. To do so, field work has been done to map local geology, geomorphological features related to the landslide activity, and to carry out the damage inventory. We wanted to test the suitability of using a short set of "ENVISAT 2010+" project SAR images to monitor surface displacement in this urban environment. We have processed nine descending acquisitions, taken from April 2011 to February 2012, applying the multi-temporal interferometric analysis method developed in [29,30]. In the landslide case, additional monitoring data from classical techniques was available, so we were able to study the temporal evolution of displacements from September 2008 to November 2009.

2. Study Area

2.1. Geography

Arcos de la Frontera is a monumental and touristic town located in the northern half of the province of Cádiz (Andalusia, Spain). The geomorphology of the settlement is dominated by the meander-shaped channel of the Guadalete River, which has carved the 100 m crag where the historic

center was raised centuries ago [31]. Since the '50s, the town has doubled its extension, mainly towards the northwest (Figure 1), and the population has increased by around 40%. Urban expansion was accelerated from the late '90s until 2010, coinciding with the Spanish housing bubble.
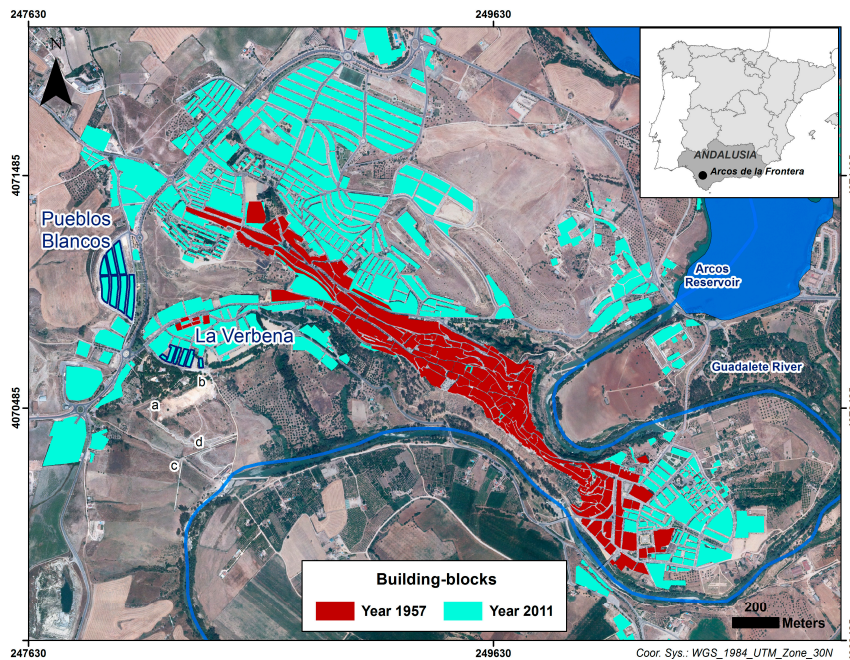
Figure 1. Arcos de la Frontera location. Urban expansion from the '50s to the present can be appreciated through the depicted blocks of buildings. The La Verbena and Pueblos Blancos buildings are depicted in dark blue.

The typology of the new construction differs from the traditional architecture and consists mainly of low-rise blocks of buildings. La Verbena and Pueblos Blancos are two neighborhoods located in the new residential areas. Their buildings have two or three store levels above ground, plus a basement floor intended for a car park and/or storage. The La Verbena neighborhood was built between 2001 and 2004, and consists of five buildings containing around 190 family dwellings. It is located on the medium part of a slope oriented towards the SE that faces the Guadalete River. The angle of this slope ranges from 55° at the top, to 18–23° at La Verbena site, and 14° at the river level [32], which is related to the type of geological material as it is shown in the following subsection. Pueblos Blancos is located northwest of La Verbena and it was constructed on man-made fill that was placed in order to level the topography of a low gradient slope oriented towards the northwest. This neighborhood was constructed between 2001 and 2006, and is formed of seven buildings (two of them were not totally finished) with around 320 family dwellings and commercial spaces.

2.2. Geological and Geotechnical Context

Arcos de la Frontera is located within a small Neogen-postorogenic intramontane basin in the western border of the Subbetic range system. The local geology and geomorphology were mapped in field surveys for the present work (Figure 2). Geological materials are characterized by Quaternary alluvial deposits from the Guadalete River and the following upper Miocene lithologies, marine in origin [33]:

- Calcarenites and sandstones, commonly known as "Caliza Tosca" of Arcos de la Frontera, which constitute the upper part of the slope that faces the Guadalete River (with a slope angle of about 55°) and the crag where the old town is located.

- Silts, marls and sandstones, which outcrop in the middle part of the slope (18–23°) where La Verbena is located and also determine the substratum where Pueblos Blancos settles, below the artificial filling.
- Blue marls with narrow intercalations of sands, which develop typically smooth slope landscapes (<15°). They outcrop in the lower part of the slope facing the Guadalete River.
- White marls with siliciclastic sands, which outcrop in the east of the studied area.
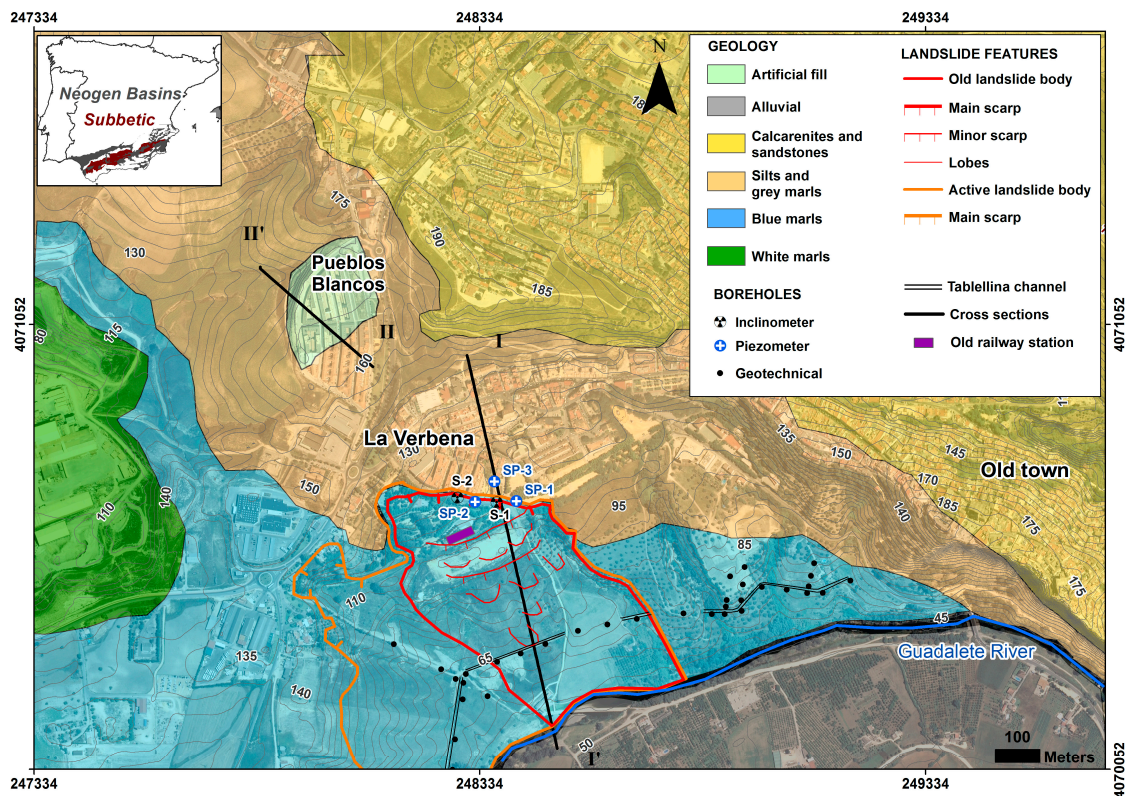
Figure 2. Local geology of the studied area. Old and active landslide features are identified. The Tablellina water channel trace is discontinuous because it is partially buried.

The artificial man-made fill that bears Pueblos Blancos was placed in 2001; it consists of loose materials composed by clayey marls [34] and calcarenite boulders, and it reaches more than 20 m in thickness.

Special attention has to be paid to blue marls, also known as the Guadalquivir Blue Marls (GBM) or Guadalquivir Blue Clays, because they typically undergo serious geotechnical problems [35–38], mainly related to shallow slope instabilities as well as deep seated landslides, subsidence, collapse, soil creep and expansiveness. They are extensively present along the Guadalquivir Basin generating multiple damages in the region. GBM are mainly constituted by phyllosilicates (smectite, illite and kaolinite) with a calcium carbonate content over 20% [37] and they are strongly affected by mechanical weathering which is responsible of drastic changes in their geotechnical properties and their behavior. When unweathered, blue marls possess high consistency and resistance, so they can be classified as a stiff soil or a soft rock [39]. However, when weathered, their shear strength is drastically reduced. The worsening of the geotechnical properties is caused by microstructure alteration without significant chemical compositional variations [37]. The alteration process consists in the transformation of the fabric from compact and dense to open and chaotic, and it can be explained by changes of the internal stress conditions due to the combined action of confining stress release and swelling pressure of the clay matrix. Cracks and fissures formed by contraction and shrinking are commonly present at

the GBM surface; they facilitate the penetration of desiccation during drought periods and water percolation during rainfall periods, feeding back the alteration process. Natural slopes of GBM can show instability signals even in gentle slopes, with inclinations as low as 10° [39]. We have identified the geomorphological features of old instabilities in the slope facing the Guadalete River (Figure 2).

2.3. Geotechnical Campaigns in La Verbena landslide

A total of 44 geotechnical boreholes, up to 70 m deep, were performed in previous works [40] along the Tablellina water channel which goes across the lower part of the main body of the landslide (Figure 2). Two lithotechnical units were identified: a weathered GBM layer at the top, with a thickness that varies from 19 m to 2 m (being thicker at the old landslide area), and an unweathered GBM layer beneath it, the footwall of which was not detected in any borehole. Identification laboratory tests were performed in unaltered samples and the geotechnical parameters are shown in Table 1. No direct expansivity test were done, however the liquid limit and plasticity index values indicate high swelling potential [41].

Table 1. Average physical/chemical parameters of a total of 17 Guadalquivir Blue Marls (GBM) weathered and unweathered samples taken along the Tablellina channel [40].

Parameter	Weathered GBM	Unweathered GBM
Liquid Limit	44.8	60
Plasticity Index	21.3	32.7
In situ density (g/cm^3)	1.60	1.55
Humidity (%)	20.9	25.6
Specific weight (g/cm^3)	2.75	2.74
%CO_3Ca	34.88	28.57
%SO_3	0.74	0.19

More recent geotechnical campaigns were focused on the La Verbena neighborhood [42,43], in which two inclinometers (S-1 and S-2) and three piezometers were installed (Figure 2). Continuous core samples of the soil were recovered before placing the inclinometric devices, and the materials were identified as silts and grey marls [43]. Two readings were performed between September 2008 and February 2009. Inclinometer S-1 (25 m length) detects terrain shear at 24 meters deep and around 30 mm of cumulative terrain motion towards the maximum slope direction, while in inclinometer S-2, the slip rupture was clearly detected at 6 m deep showing cumulative displacements of less than 30 mm towards the maximum slope direction (Figure 3). Crack monitoring gauges were installed inside the most damaged buildings of the La Verbena neighborhood [44,45]. Two periods were monitored, one from 18 March 2009 to 1 June 2009 and the other from 14 July 2009 to 16 November 2009. The maximum recorded displacements were 4.47 mm and 5.3 mm, respectively (Figure 3). The phreatic level was measured in 11/09/08 at both inclinometric boreholes, this was at 9 m depth at S-1, while S-2 was dry. The only data available from the piezometers was the phreatic level measured on 3 September 2010, which was at 2.5 m depth at SP-1, 4.5 m depth at SP-2, and 3.2 m depth at SP-3. These phreatic level measurements were taken two years apart. In that period of time a heavy rain period occurred, starting in December 2009 and lasting until February 2010, which explains the rise of the water table of almost 5 m. During those three months, a total amount of 670 mm of rainfall was measured at the Jerez de la Frontera meteorological station [46] (located 30 km from the studied area). This is a much higher value than the average accumulated rainfall for the same season, registered from 1980 to 2012, which was 252.4 mm.
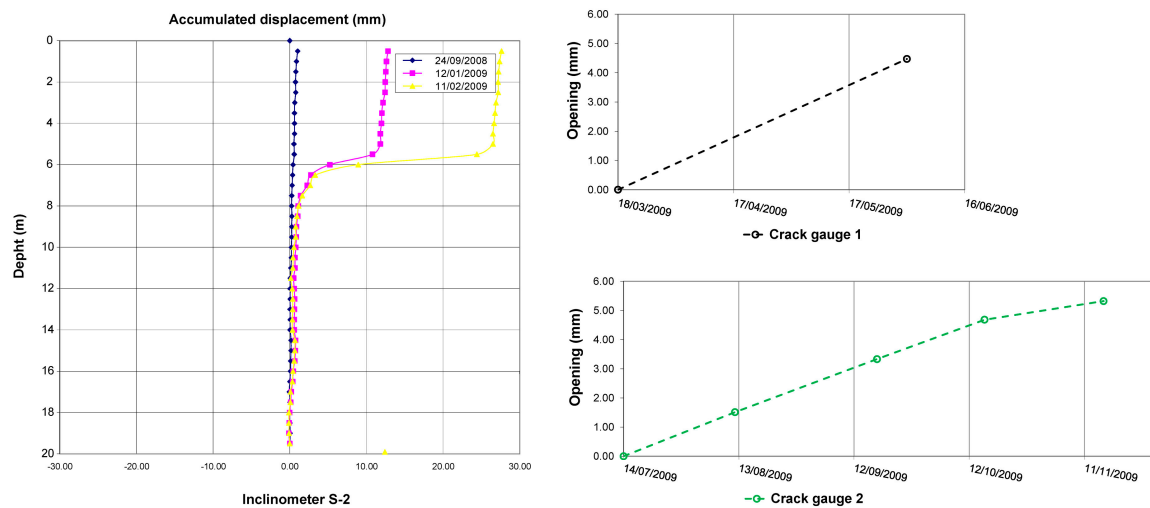
Figure 3. Graphs of the accumulated deformation measured at the inclinometer S-2 (modified from [42]) and maximum opening of cracks measured in the indoor walls of the most damaged building.

3. Arcos de la Frontera Landslide

3.1. Classification and Activity

The Arcos de la Frontera landslide develops in weathered GBM on the lower part of a slope whose base is being eroded by the Guadalete River (Figure 2). The landslide extension is around 0.17×10^6 m^2 and the direction of the movement is southeast, towards the river. Regarding the style of the activity, it can be classified as a retrogressive landslide, since the surface of rupture is extending in a direction opposite to the movement of the displaced material [17]. Evidence of retrogression are the presence of older crown features downslope and lobular morphologies at the toe (Figure 2). The presence of cracks at the surface and the high permeability of weathered GBM permit water percolation, which can trigger a rapid response of the landslide to daily rainfall. According to Cruden and Varnes' movement classification [17], the landslide has a very slow velocity.

### 3.2. Damage in La Verbena Area

The Arcos de la Frontera landslide activity has been causing severe damage to infrastructure for decades. In the '70s, landslide motion was provoking the deterioration of the Tablenilla irrigation water channel located at the foot of the slope (Figure 2). The old railway station and rail track area that is currently occupied by a park were also affected by the same process (Figure 4a–c). A geological study was carried out in order to evaluate slope instability [40], which concluded that the water channel had to be buried through a non-weathered GBM formation, as shallow landslide processes were taking place in the weathered GBM layer and damages were expected to worsen during intense precipitation periods. The water channel has undergone stability problems since then and various remedial works have been carried out along its trace [47,48], with the latest one in 2011 [49]. In 2015 we detected cracks and bulks along the channel, which indicate landslide activity in the area (Figure 4d).

Figure 4. (**a**,**b**) Damaged railroad close to the old railway station [40]. The slope was affected by numerous landslides in the weathered layer of the GBM. (**c**) Detail of a crack presented in the Tablellina irrigation water channel, located in the low part of the slope [40]. (**d**) Cracks and bulks in the Tablellina water channel in 2015. The location of the photographs is labelled in Figure 1.

The La Verbena neighborhood is formed by five buildings located in the landslide crown-area and is cross-cut by the main scarp. Nonstructural damages, such as cracks in common and private zones and the opening of the dilatation joints, started soon after it was constructed [50]. Local remedial works were carried out, but in 2007 structural problems were detected in at least one of the buildings [51]. The downslope motion was progressively damaging sewer and water systems, pillars, partition walls, foundations and roads [52]. The most affected building (building f in Figure 5) housed 22 families and is divided in two by a dilatation joint. In October 2009, it was evacuated due to severe structural damages caused by landslide motion, as one part of the building had tilted with respect to the other, having reached a separation of more than 1 m (Figure 5f). Short after, an intense precipitation period spanning December 2009–March 2010 triggered the acceleration of the landslide, which aggravated the state of building f, declared derelict in March 2010 [53]. Adjacent buildings, public areas and water supplies were also affected during this period (Figure 5g–i). Local and national authorities compromised to repair urban damage and stabilize the landslide in 2010. Remedial works were planned to consist of two phases that started in 2011 and concluded in 2014, including the drainage of the slope, sewage network repair and reinforced grouting, with a total estimated cost of around 2.6 million euros [54–56]. A third phase of remedial works is currently being planned [57]. Considering standard housing prices, the economic loss to the dwelling owners of the run-down building amounts to 1.3 million euros.
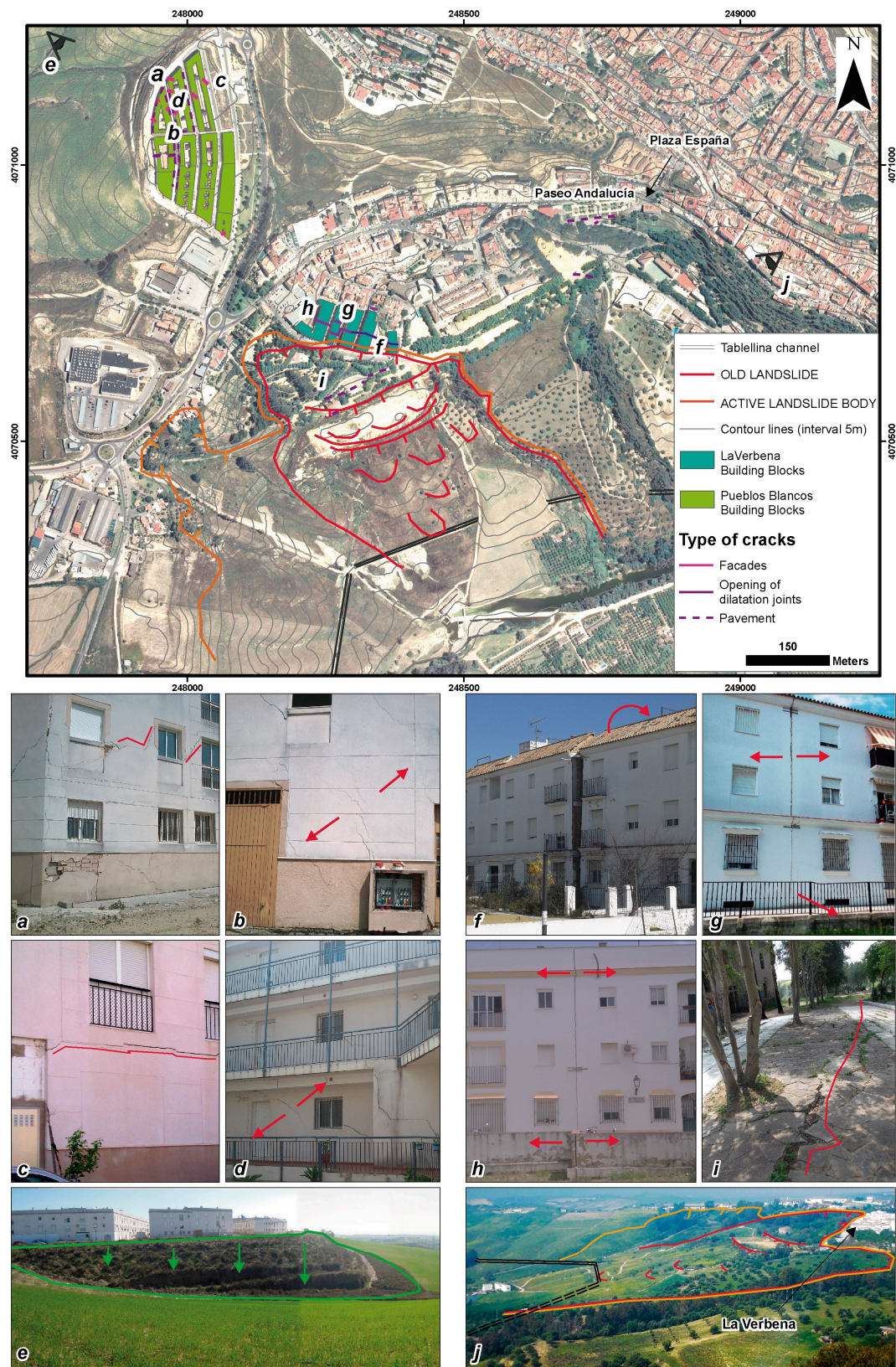
Figure 5. Inventoried cracks layout of La Verbena and Pueblos Blancos neighborhoods along with main landslide features. (**a**–**e**) Pueblos Blancos: 45° angle dip and horizontal cracks in facades and in the internal patios and general view of the earth fill undergoing differential compaction. (**f**–**j**) La Verbena: building tilting, opening of the dilatation joints, pavement disrepair caused by numerous cracks at the head of the scarp (old train station location) and general view of the Arcos de la Frontera landslide.

4. Pueblos Blancos Site. The Case of the Differential Settlement of an Artificial Fill

The Pueblos Blancos neighborhood is formed by a set of seven buildings founded on an artificially man-made fill that was placed to level the topography of a gentle slope. The main pathology affecting the buildings in this area is not related to landslide activity, but to the differential settlement caused by the uneven compaction of the filling materials (Figure 5). The filling reaches a thickness of more than 20 m and is composed of clayey marls [34] and calcarenite boulders.

The main damages present in Pueblos Blancos buildings are cracks on facades and walls, a with 45°-dip angle and horizontal and vertical directions. We also detected damages in non-structural elements such as parapets, ledges, stairs, windows, door frames and banisters. Damages are present outdoors, indoors and on the internal patios, as well as in the street pavement (Figure 5a,b,d). The layout of the crack distribution shown in Figure 5 indicates a progressive worsening of damage towards the northwest. The most deteriorated buildings are those located in the area where the thickness of the filling is greater, between the Tango and Seguirilla streets (labeled in Figure 5). Stabilization measures, with an estimated cost of 3 million euros [58], were carried out in 2009 [59]. They consisted of pile driving the most affected areas, drainage measures, and the construction of an anchored wall. However, we have detected surface displacements in Pueblos Blancos for the period 2011–2012, as discussed in the next section, and ongoing building deterioration between 2013 and 2015 by visual inspection. In both field campaigns we noticed that an entire block is uninhabited, one was semi abandoned due to deterioration and the streets surrounding them was closed to traffic as a result of disrepair.

5. A-DInSAR Monitoring

5.1. "ENVISAT 2010+" Project Images Processing

Differential synthetic aperture radar interferometry (DInSAR) is a remote sensing technique for monitoring deformation episodes of the earth surface with millimetric precision in the best case scenarios [30,60–62]. It uses synthetic aperture radar (SAR) complex reflectivity images, which are collected in all-weather conditions by space-borne sensors. DInSAR techniques are based on exploiting the phase differences between multi-temporal pairs of SAR images from the same area of study, thus permitting the precise monitoring of ground displacements in the line-of-sight (LOS) direction [63]. The limitations of traditional DInSAR techniques, related to temporal and geometric decorrelation, topographic residues and atmospheric artifacts [30,63], have been partially solved by Advanced DInSAR (A-DInSAR) techniques, which use a stack of images instead of pairs and extract the temporal evolution of the deformation. These techniques can be divided into two methods according to how targets are selected, in order to obtain the time series displacements: prevalent phase-coherent radar targets by amplitude stability or persistent scatter (PS) methods [64] and distributed targets by spatial coherence or small baseline subsets (SBAS) [65–68]. Although the persistent scatter approach is normally better suited for urban areas due to the high reflectivity and low decorrelation in time of man-made constructions such as buildings, a minimum number of about 30 acquisitions is required [64].

For this work, we wanted to test the suitability of using "ENVISAT 2010+" project SAR images to monitor surface displacements in the Arcos de la Frontera urban environment. For the "ENVISAT 2010+" project, the orbit of the satellite was lowered from about 800 km to about 783 km in order to conserve fuel and extend its life. The incidence angle of the radar signal was increased from 23° to 35°. The new orbit project started on 22 October 2010 and lasted until communication with the ENVISAT satellite was suddenly lost on 8 April 2012.

A set of nine SAR descending orbit images was available from the ESA archive, covering the period April 2011 to February 2012 (Table 2). We have ensured that the target area is visible by the side look acquisition mode of the ENVISAT antenna for the descending mode. A small baseline (SBAS) approach was used to study surface displacement behavior in Arcos de la Frontera. The reason for this

was that small baseline algorithms require a reduced set of images compared to the PS method [66], due to their capability to generate a larger number of interferograms, as they allow the combination of all available images that satisfy a baseline length and time interval values (which are set up to reduce spatial decorrelation). On the contrary, all interferograms generated by PS algorithms are formed with respect to a single "master" SAR image, so for N SAR images a number of N-1 interferograms will be obtained.

Table 2. Acquisition dates and perpendicular baselines with respect to the master of the Synthetic Aperture Radar (SAR) images from the "ENVISAT 2010+" project used in Advanced DInSAR (A-DInSAR) processing.

SAR Image	Acquisition Date	Perpendicular Baseline [m]
1	15 April 2011	151
2	15 May 2011	474
3	14 July 2011	61
4	13 August 2011	0
5	12 September 2011	133
6	12 October 2011	94
7	11 December 2011	−210
8	10 January 2012	282
9	9 February 2012	156

SAR scenes were cropped to an area of about 9 km^2, co-registered to a common master geometry, and differential interferograms were computed using DORIS software (Kampes et al., 2003). To remove the topographical contribution, a 5 m resolution Digital Elevation Model (DEM) from the Geologic National Institute of Spain (IGN) was used. A spatial multilooking factor of 1:5 (range × azimut) was applied, producing pixels sizes of about 20 × 20 m in the ground. The average spatial coherence threshold used was 0.75, which is a quite restrictive value that has been chosen due to the small multilook factor. With these inputs, a total of 4579 pixels were selected. The mathematical model MTIANPAC (Multi-Temporal Interferometric ANalysis PACkage) was used to retrieve the mean velocity and time series displacements [29,30]. A total number of 30 interferograms were generated from the nine SAR images using spatial baselines (B$_{perp}$) below 400 m (Figure 6).
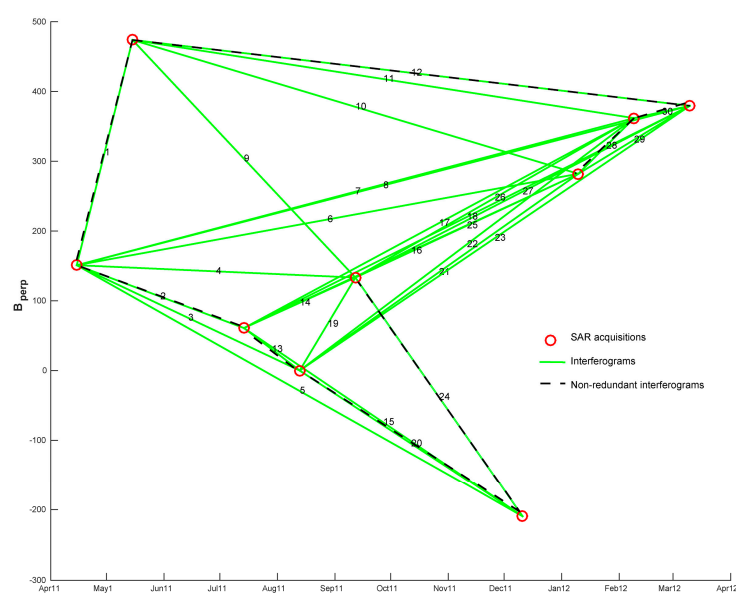

Figure 6. Connection map of the 30 interferograms generated using a spatial baselines (Bperp) below 400 m.

Recent investigations have highlighted the potential importance of phase inconsistency during SBAS multilooking operations causing phases biases [69]. Our analysis neglects phase inconsistency, however the exact reasons for the inconsistencies are not yet well understood, ranging from volumetric scattering to seasonal effects, implying that our InSAR results could not be due to ground motion (e.g., landslide activity). Nevertheless, we expect this effect to be smaller for stable targets such as urban areas, and larger for natural terrains.

5.2. A-DInSAR Results

The results of the accumulated LOS displacement obtained with A-DInSAR are shown in Figure 7a, with positive values indicating movement towards the satellite. Pixel density is around 1600 pixels/km^2, which is a relatively high value for C-band data, but is constrained to urbanized sectors. No prevalent phase-coherent radar targets were detected in vegetated areas, nor in the main body of the La Verbena landslide, as coherence is almost completely lost due to temporal decorrelation. However, pixels were detected at the crown of the landslide, which is urbanized.
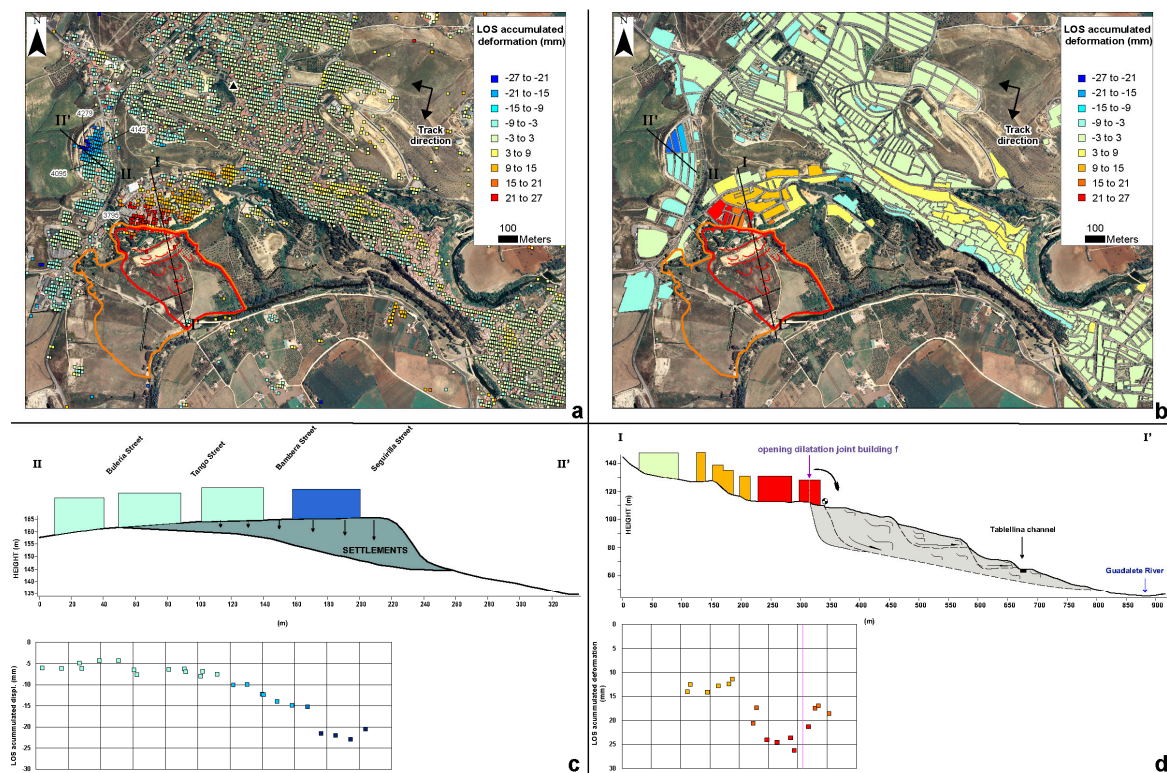
Figure 7. (**a**) Accumulated line-of-sight (LOS) displacement map. The reference point used for A-DInSAR processing is marked with a black triangle. (**b**) city block accumulated LOS displacement for the period April 2011–February 2012. Positive values indicate movement towards the satellite. Black arrows at the upper right of the scenes indicate the descending track direction of the satellite and right-looking mode. Landslide features and the Tablellina channel are depicted in both scenes. (**c**) Pueblos Blancos cross section with buildings (earth fill in green) and projected accumulated LOS displacement pixels along the cross section line II–II'. (**d**) La Verbena landslide cross-section with buildings (depleted mass in grey) and projected accumulated LOS displacement pixels along the cross section line I–I'. Building f and inclinometer S-1 are depicted (Figure 5f).

The standard deviation of the accumulated LOS displacement was 5.5 mm, considering all pixels of the studied area. The highest displacements rates were located in the Pueblos Blancos and La Verbena areas, while in the old town most of the values comprised between −3 and 3 mm. We consider

that the old town is stable because there is no urban damage related to landslide or subsidence activity and the substrate where it settles is formed by a competent lithology compared to that of Pueblos Blancos (loose fill) and the La Verbena landslide (GBM). We calculated the accumulated LOS displacement of all the pixels included within the area defined by every building or block of buildings (Figure 7b) in order to study the relation of the movement amount to the degree of damage. The polygons that define each building or block of buildings were extracted from a 1:1000 cartographic map. A buffer of 20 m was used around the polygons in order to include adjacent pixels in the calculation. To support the visualization of the results, we projected the accumulated LOS displacement pixels (with a 20 m buffer) along representative cross sections of Pueblos Blancos and La Verbena, lines II–II′ in Figure 7c and I–I′ in Figure 7d, respectively. Line I–I′ crosses building f, which was declared derelict due to severe structural damage caused by landslide motion. The LOS displacement time series for a couple of selected pixels for Pueblos Blancos and La Verbena are shown in Figure 8.
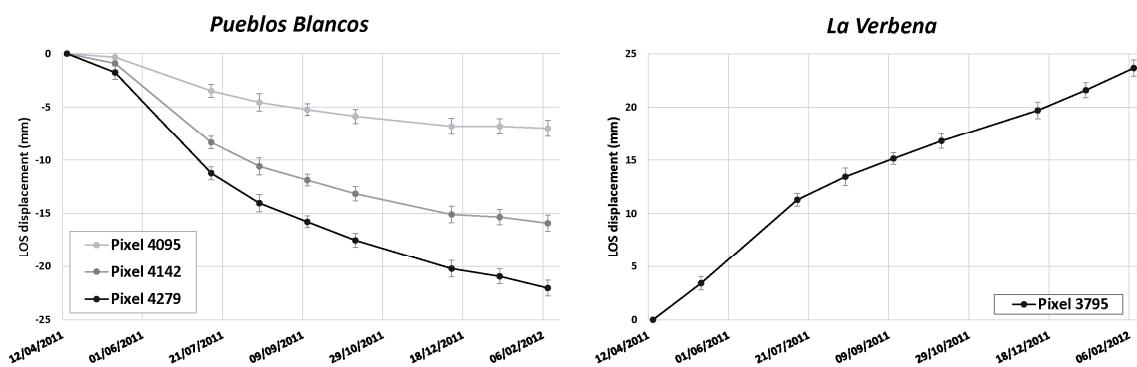
Figure 8. LOS deformation time series for a number of pixels for Pueblos Blancos and La Verbena. Their location is labeled in Figure 7.

6. Discussion

The impact of hazards posed by unstable terrain increases in urban settlements, due to the social exposure and economic implications. In this work, we presented an interesting case of the application of DInSAR monitoring techniques to map slow-moving ground motion that affects urban areas. This approach has provided evidence of the spatial distribution of two deformation phenomena occurring in the newer part of an Arcos de la Frontera town, and which are related to different unstable ground processes. One of these processes is a very representative case study of the gentle slope landslides associated with the GBM geological formation, which is extensively present along the Guadalquivir basin and typically undergoes serious geotechnical problems.

The deformation phenomena detected with A-DInSAR in the Pueblos Blancos neighborhood is related to the compaction process of loose artificial earth filling. The measured accumulated LOS displacement reached −33 mm. The negative sign indicates movement away from the satellite due to subsidence or vertical negative displacement. The magnitude of the measured displacement increases progressively towards the northwest, which correlates with the gradual increase of the earth fill thickness (Figures 7c and 8), as well as with the degree of building deterioration (Figure 5). The orientation of the 45° angle dip cracks of the facades also indicate that the compaction of the loose earth fill produces more settlement towards the northwest, which is congruent with the A-DInSAR results. Remedial solutions (micropiles among others) were carried out before the A-DInSAR monitoring period.

The La Verbena neighborhood is located at the crown of the Arcos de la Frontera active landslide. Taking into account that the positive sign of the velocity indicates movement towards the satellite, we interpret the A-DInSAR measurements as showing landslide displacement towards the southeast, projected along the satellite line-of-sight (LOS). The accumulated LOS displacement reached up to

33 mm. We decided not to project the measured velocities along the slope direction, because the nearly flat topographical gradient (below 5°) in the urbanized area where coherent pixels are detected would provide an anomalous solution. The measured displacement at the crown of the landslide indicated that the surface of the rupture is extending in the direction opposite the movement of the depleted material. This behavior is consistent with the old retrogressive features we mapped in field surveys. The buildings around the La Verbena area show accumulated LOS displacement that ranges from 15 to 33 mm depending on their proximity to the landslide crown. The opening of the dilatation joints in the La Verbena buildings (Figure 5) mark the outcropping of the new main scarp. In the cross section of Figure 7d it can be noticed that the velocities are greater above this feature, again confirming the retrogressive nature of the landslide, as the crown is moving forward at a greater rate than the depleted mass. Inclinometer S-1 shows terrain motion but a deeper borehole should be drilled to clearly detect the slip surface. In inclinometer S-2 the slip surface was detected at 6 m depth. This suggests that at least two rupture planes were developing within the same landslide, a shallower one at the S-2 location and a deeper one at S-1. The displacement rates of both inclinometers are similar [42].

From the first day of December 2009 to the last of February 2010, 670 mm of accumulated daily rainfall was recorded at the Jerez de la Frontera meteorological station. During this exceptional rain period, the aggravation of damage to La Verbena buildings and the surroundings (located at the crown of the landslide) were observed [52,54–56]. This suggests a rapid cinematic response of the landslide to water infiltration. The high permeability of the weathered GBM and the presence of cracks at the surface of the landslide body permit water percolation which can accelerate the motion. We do not have landslide monitoring data available for that period, however we have data from in situ monitoring techniques before this event and from A-DInSAR after it. Inclinometers registered around 30 mm of rigid motion above the rupture plane in 140 days towards the maximum slope direction (Figure 3), from which we can extract an average velocity of 78 mm/yr. During those 140 days a total of 414 mm of rainfall was recorded at the Jerez de la Frontera meteorological station, which gives an average rainfall of 3 mm/day. Crack monitoring gauges registered a rate of opening of indoor walls fissures of 21.7 mm/yr with an average daily rainfall of 0.9 mm/day for the period 18 March 2009 to 1 June 2009, and 16 mm/yr with an average daily rainfall of 0.4 mm/day for the period 14 July 2009 to 16 November 2009 (Figure 3). We retrieved an average LOS displacement rate of around 30 mm/yr in the most affected areas of the La Verbena neighborhood for the period 15 April 2011 to 9 February 2012, for which the average daily rainfall was 1.1 mm/yr. We observe that the rate of displacement increased with the accumulated daily rainfall. However, in order to perform a reliable correlation between landslide motion and rainfall, longer and more continuous displacement monitoring sampling would be needed.

7. Conclusions

The Arcos de la Frontera urban site is a relatively small area where two neighborhoods constructed on unstable terrain have been severely damaged in recent years. Buildings in the La Verbena neighborhood are being affected by the retreating of the head-scarp of a large landslide developed in Guadalquivir Blue Marls (GBM). The Pueblos Blancos neighborhood is affected by the uneven compaction of the loose artificial earth filling on which it stands, which causes differential building settlement.

The application of A-DInSAR techniques with a small baseline approach and the exploitation of a short set of C-band images proved to be a useful tool for the detection of the surface displacements induced by different geotechnical processes in Arcos de la Frontera. The highest displacement rates detected by A-DInSAR were in the order of 30 mm/yr. The amount of displacement is directly related to the degree of damage. Displacement at Pueblos Blancos indicates movement away from the satellite caused by negative vertical movement, which is due to the differential building settlement associated with the uneven compaction process of a loose earth fill. The amount of displacement and the degree of damage increased progressively towards the northwest edge of the neighborhood, where the thickness

of the earth fill is higher and therefore the settlement will be greater. It was shown that remedial solutions to stop differential settlement did not work properly, as the A-DInSAR monitoring was performed after they were carried out. Displacements measured with A-DInSAR at the La Verbena neighborhood indicate downhill movement and are related to the Arcos de la Frontera landslide process. The spatial distribution of the pixels indicates high displacement rates in an elongated area parallel to the main scarp of the landslide, which coincides with the most degraded buildings and is associated with the retrogressive landslide mechanism. Landslide displacement rates suggest that velocity is directly related to rainfall. Another factor influencing landslide stability is toe erosion by the Guadalete River along the base of the slide mass, as the slope where it develops is located on the outside bend of a meander (high energy bank). Velocities measured with different monitoring techniques range from around 16 mm/yr to 78 mm/yr. During the winter 2009–2010, an intense rainy period caused severe structural damage to buildings and infrastructure, although no monitoring data is available for that period.

Regarding the use of ENVISAT SAR images after 2010 (ENVISAT2010+ project), we can establish that they will be useful for detecting different geotechnical processes at other urban sites with similar characteristics to Arcos de la Frontera, besides decorrelation due to vegetated areas and the limited number of images. Note that the 35° incidence angle permits the selection of more measurement pixels than the 23° angle for an SBAS approach, which is the most suitable DInSAR approach when few images are available. This can be explained because a greater incidence angle implies that reflectivity will be lower (less signal amplitude will be reflected back to the satellite), but also that it will be more coherent. The more vertical the incidence angle (23°), the more objects will reflect back the signal to the satellite but in a random way, which will mean less coherence.

The enhanced spatial resolution of the current active C-band satellite Sentinel-1, of the European Space Agency (ESA), could also be exploited to monitor problematic areas in Arcos de la Frontera in the future. A conclusive advantage of Sentinel-1 products with respect to X-Band SAR systems, such as the TerraSAR-X constellation of the German Space Agency (DLR) or the COSMO-SkyMed constellation of the Italian Space Agency (ASI), is that the ESA has an open distribution policy, offering free and open access to Sentinel-1 data. The higher spatial resolution and less revisiting time of this satellite would be suitable to measure the differential deformation of different sectors of single buildings. Angular distortions caused by differential settlement processes, where only vertical displacement is assumed, could be investigated [24,26]. Furthermore, it can be used as a tool to monitor possible displacements after remedial stabilization solutions have been carried out.

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