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The combined use of PSInSAR and UAV photogrammetry techniques for the analysis of the kinematics of a coastal landslide affecting an urban area (SE Spain)

Abstract In the present work, the case of the Cármenes del Mar resort (Granada, Spain) is shown. It can be considered one of the most extreme examples on the Mediterranean coast of severe pathologies associated with urban development on coastal landslides. The resort, with 416 dwellings, was partially built on a deep-seated landslide which affects a soft formation composed of dark graphite schists. In November 2015, the City Council officially declared a state of emergency in the resort and 24 dwellings have already been evacuated. We have used two remote sensing techniques to monitor the landslide with the aim of identifying and measuring a wide range of displacements rates (from mm/year to m/year): (1) PSInSAR, exploiting 25 ENVISAT SAR images acquired from May 2003 to December 2009, and (2) photogrammetry, considering the output from two Unmanned Aerial Vehicle (UAV) flights made in June 2015 and January 2016 and the outdated photos from a conventional flight in 2008. The relationship between the geology of the site, data from PS deformation measurements, building displacements, rainfall and damage observed and their temporal occurrence allows a better understanding of the landslide kinematics and both the spatial and temporal evolution of the instability. Results indicate building displacements of up to 1.92 m in 8 years, a clear lithological control in the spatial distribution of damage and a close relationship between the most damaging events and water recharge episodes (rainy events and leaks from swimming pools and the water supply network). This work emphasises the need to incorporate geohazards into urban planning, including policies to predict, prepare for and prevent this type of phenomenon.

Keywords Landslide · Urban development · Damage · PSInSAR · UAV photogrammetry · Mediterranean coast

Introduction

In recent decades, building damage caused by landslides in urban areas has increased due to the rapid growth of urbanisation on landslide-prone slopes in the Mediterranean region (Antronico et al. 2015; Faccini et al. 2015; Bianchini et al. 2013; Mateos et al. 2013; Jimenez et al. 2012). In Spain, new urban areas have spread to natural coastal areas, ranging from cliffs to alluvial plains and deltas as the Spanish economy depends largely on income from construction and tourism (Mateos 2007). On the Mediterranean coast of Andalusia, the slopes of the Betic Mountains near the coast produce very narrow coastal plains and urban development has extended onto very steep areas with pre-existing and dormant landslides. Coastal landslide zones are coveted by construction companies because these places not only provide elevated areas with excellent sea views but they also provide a more gentle slope than the adjacent, stable zones and are thus assessed as more favourable for development (Cascini et al. 2005).

The municipality of Almuñécar (Granada), located on the SE part of the Mediterranean coastline of the Iberian Peninsula (Fig. 1), has a long history of economic and social losses related to landslide activity. Notti et al. (2015) recently reported the case of the Marina del Este resort, where severe urban damage has occurred due to the reactivation of a pre-existing coastal landslide.

The present research is focused on the Cármenes del Mar resort, located in the protected natural area of the Cerro Gordo Promontory, on the western side of La Herradura beach and 3 km from the Marina del Este site (Fig. 1). Both places present similar geological and geomorphological conditions and urban development was carried out on steep slopes with old landslide features (Fig. 2). At the time of writing, 24 dwellings which lie in ruins have already been evacuated in the Cármenes del Mar resort and the City Council officially declared a state of emergency in November 2015, causing great social alarm. The evacuation will be extended to 40 more dwellings in the coming months.

The case of Cármenes del Mar is currently subject to judicial proceedings and a large amount of technical information is sub judice. The present work brings together detailed field surveys made in the study area as well as certain information from disclosed technical reports (Vorsevi 1998; Ortega-Espinosa 2010; Rodríguez-Ortiz 2011).

Monitoring and analysis of active landslides involves both spatial and temporal measurements and requires continual assessment of landslide conditions, including the extent and rate of displacements as well as changes in the surface topography (Niethammer et al. 2010). With the aim of monitoring slope activity, Synthetic Aperture Radar (SAR) images taken by ENVISAT during the period 2003–2009 were used. The deformation measurements were derived using the Persistent Scatterer Interferometry (PSI) approach, described in Crosetto et al. (2011).

In urban areas, displacement rates of buildings are of great interest and can be directly obtained by comparing orthophotographs as well as digital surface models (DSMs) from different dates. In recent years, the application of Unmanned Aerial Vehicles (UAVs) has become a very valuable tool in remote sensing and numerous recent works demonstrate their applicability for active landslide monitoring (Turner et al. 2015; Marek et al. 2015; Torrero et al. 2015; Stumpf et al. 2013; Niethammer et al. 2011). In the present research, a photogrammetric analysis has been developed using three aerial photograph sets: a conventional flight taken in 2008 and two UAV flights designed and operated in June 2015 and January 2016. Displacement vectors in buildings have been calculated to

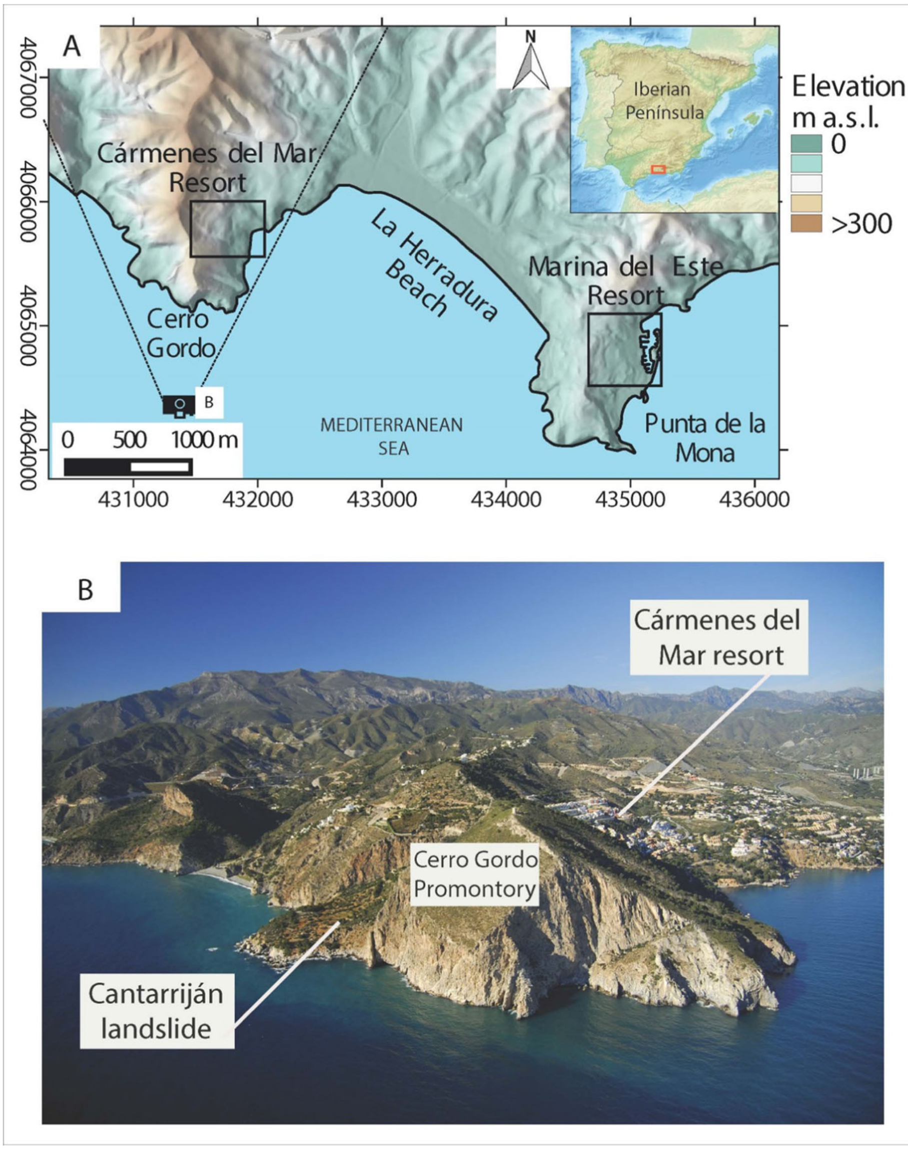

Fig. 1 **a** Geographical setting of the study area on the Mediterranean coast of Spain. The Cármenes del Mar resort was built on a steep slope on the eastern side of the Cerro Gordo Promontory and very close to the Marina del Este case reported by Notti et al. (2015). **b** Aerial photo of the Cerro Gordo Promontory. We can observe the Cantarriján landslide on its western side

quantify the deformation occurred during the last 8 years (2008–2016) and to define the more active areas in the resort with accuracy.

The main goal of this study is to determine the relationship between the distribution and evolution of the damage to buildings, the deformation measurements obtained, and the landslide kinematics. The method applied and the results obtained can contribute to the management of the resort and, specifically, to the design of the evacuation plan. The proposed case study raises challenging issues about the appropriate choices for urban areas subject to planning in coastal areas with pre-existing landslides.

Geological setting

The study area covers the Cerro Gordo Promontory (Fig. 1), a high ridge formed by metamorphic rocks that jut out into the sea. These rocks are assigned to the Alpujarride Complex (Simancas and Campos 1993) and show a deeply deformation. The rock massif includes a thrust-stack separated by major thrust surfaces producing numerous repetitions of the stratigraphy. When complete, the Alpujarride unit is typically formed, in ascending order, by gneisses and dark graphite schists (Palaeozoic), light-coloured fine-grained schists and quartzites (Permo-Triassic), and a thick Triassic carbonate sequence (Azañón et al. 1994; Azañón and Alonso-Chaves 1996; Booth-Rea et al. 2002).

Regarding the geomorphology of the area, the Cerro Gordo Promontory forms part of a rocky coast where the Triassic metamorphic rocks (mainly marbles) generate the steepest reliefs and the highest cliffs, whereas schists produce gentle slopes and a more dissected landscape. The main scarps observed in the study area generally coincide with faults that put into contact the marble formations with the schists one. Large coastal landslides are

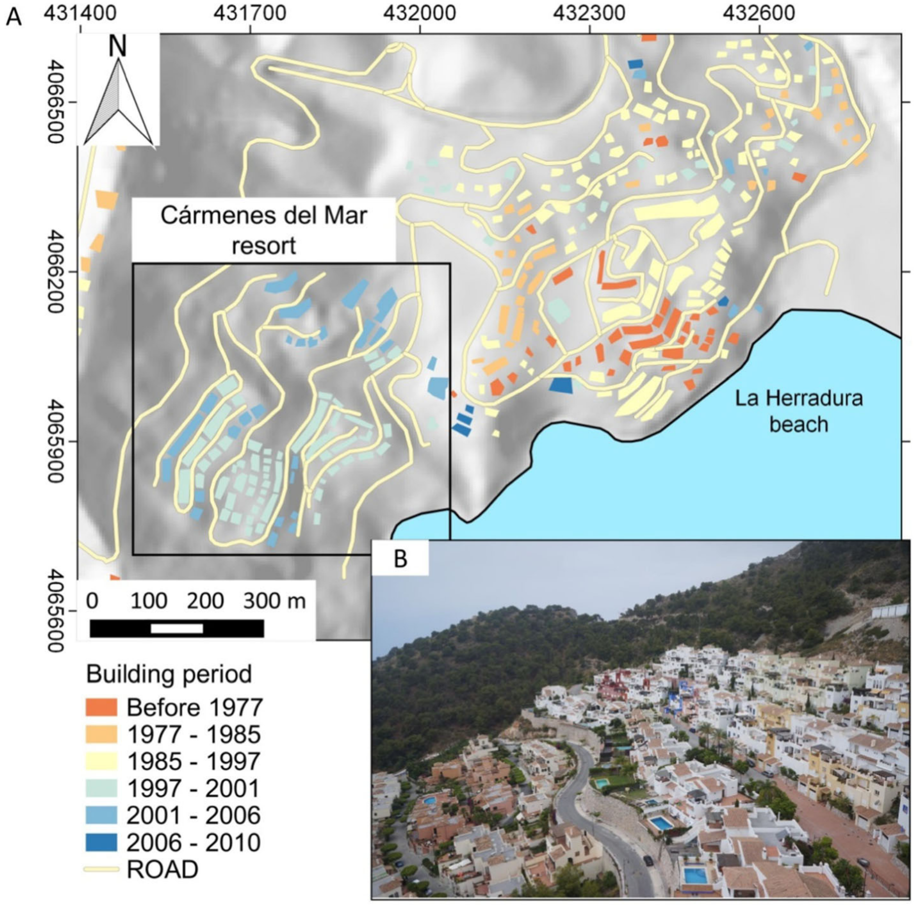

Fig. 2 **a** History of the urban development on the eastern side of the Cerro Gordo Promontory. **b** The community of the Cármenes del Mar resort consists of 416 houses (detached or terraced) as well as some communal facilities

common features along the coastline due to the instability generated by the highly tectonized and less resistant schist bedrock. The Cantarriján landslide (Fig. 1b) is a good example of this.

The geology and geomorphology of the study area were investigated, compiling previous reports (Vorsevi 1998; Ortega-Espinosa 2010; Rodríguez-Ortiz 2011), analysing historical aerial photographs and a detailed field survey was carried out. The main geological units have been mapped (at a scale of 1:1000) and structural measurements of joints, faults, and fractures have been made.

Figure 3 shows the geology of the setting. On the lower part of the slope, there are soft material outcrops, which are composed mainly of dark graphite schists and calc-schists (Paleozoic in age). This material is highly tectonized and altered, at least in the first 31.5 m (Vorsevi 1998), and the exfoliation tends to dip toward the slope. Because of their laminar structure, the materials are ductile and malleable and have a soil-like behaviour. Moisture variations materially alter their mechanical behaviour, the strength parameters decreasing the higher the water content. The main geotechnical parameters are as follows (Rodríguez-Ortiz 2011): density = 2.2 t/m^3; cohesion = 2.5 t/m^3; angle of friction = 23°. All the limits of the schist outcropping are mechanical contacts, and the rest of the slope is clearly dominated by the Triassic marbles from the Alpujarride Complex. They are predominately karstified marbles which constitutes a hard-rock substratum. Nevertheless, the rocky massif is densely fractured and numerous blocks, some of them with volumes over 300 m^3, can be observed on the slope. In fact, part of the resort (Pueblo and Especiales) was built on a chaotic debris deposit of marble blocks inserted in a granular matrix (clays and silts) which overlies the softer schist materials. The thickness of this deposit can reach up to 10 m (Ortega-Espinosa 2010) and various hanging water levels at different depths have been identified in this colluvial layer (Rodríguez-Ortiz 2011).

Structural analysis shows a normal fault oriented NNW-SSE which delimits the western lateral boundary of the schist outcropping. Moreover, the stereoplot represented in Fig. 3 shows E-W-, NE-SW- and NW-SE-oriented fractures (nearly vertical σ_1) caused the brittle deformation that determines the configuration of the present drainage pattern of the coastal belt. These mechanical discontinuities are also critical both as preference pathways to produce karstic processes and natural limits of the slope instabilities in the Cerro Gordo Promontory (Fig. 1, Cantarriján landslide). Field surveys show block spreading processes (Cruden and Varnes 1996), in the westernmost and lower part of the slope, related to the normal fault escarpment (Fig. 3). Large blocks of marble-rock seem to have moved over the schist materials. Some of them have speleothems in different positions confirming the blocks former

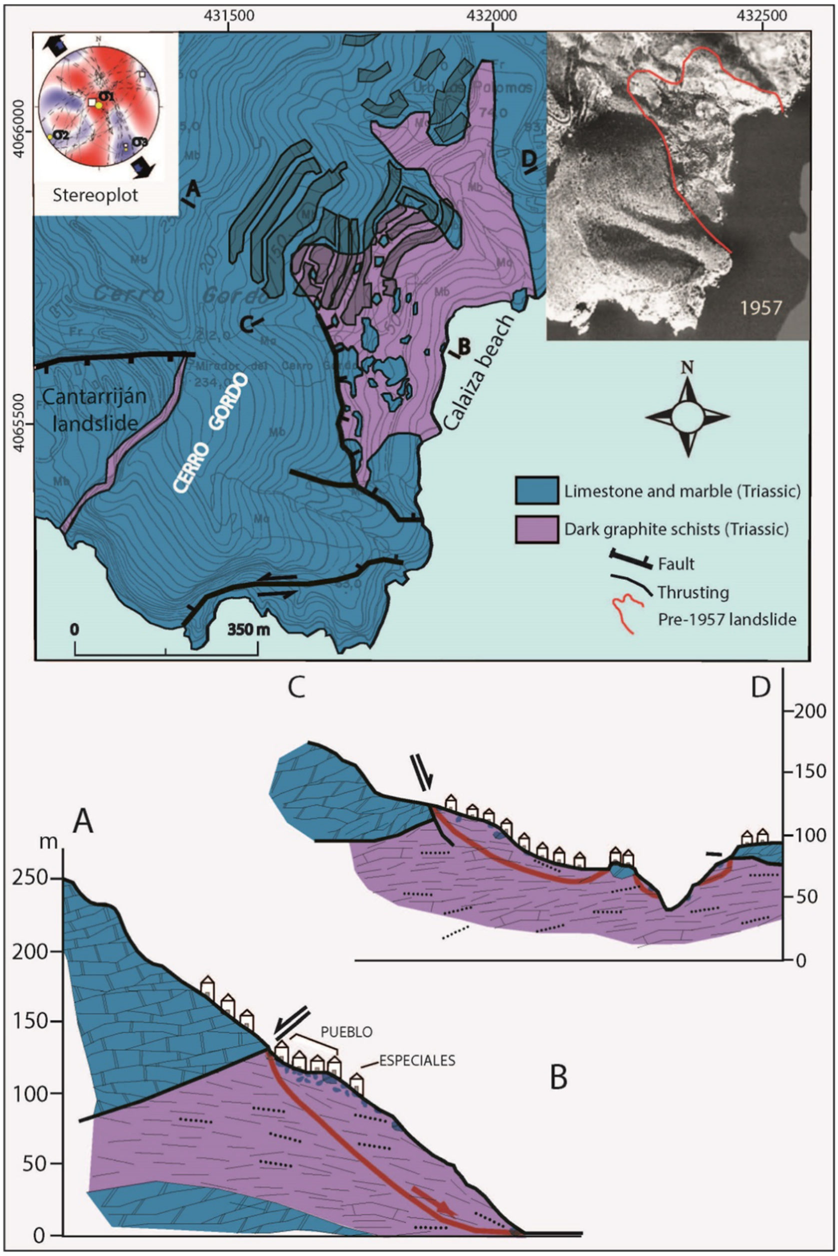

Fig. 3 Geological map of the area. The slope consists of dark graphite schist in the lower part and karstified marbles at the top. A normal fault oriented NNW-SSE delimits the schist formation on its western boundary, where lateral spreading processes have been identified. Stereoplot depicts the orientation of fractures in the area related to the most recent extensional stage. The 1957 aerial photo shows the existence of an old and large landslide in the area where the resort would later be constructed. Two geological cross sections (*A-B* and *C-D*) have been drawn to represent the disposition of the two main geo-formations and the location of the landslide failure surface based on boreholes from previous reports (Rodríguez-Ortíz 2011)

position. This area is rugged and practically inaccessible, a fact which saved it from urban development.

The interpretation of the aerial photographs taken in 1957 allows the identification of an original landslide in the landscape (Fig. 3). With an extension of around 10^4 m^2, the landslide can be mostly considered as a planar movement affecting the cataclastic and altered schist formation. The crown is located at a height of around 140 m (the geological contact between the schists and the marble formations), and the body extends until a few metres above sea level. The lateral landslide boundaries correspond to the major streams in the area. The disposition of the different geological formations in the area can be seen in the cross sections represented in Fig. 3, where the landslide failure surface has been identified at a depth of up to 40 m, based on borehole data reported in Rodríguez-Ortiz (2011).

History of urban development and damage

Urban development on the eastern side of the Cerro Gordo Promontory started around 1977 in the area nearest beach. In 1997, the western part of the slope saw development begin and it continued

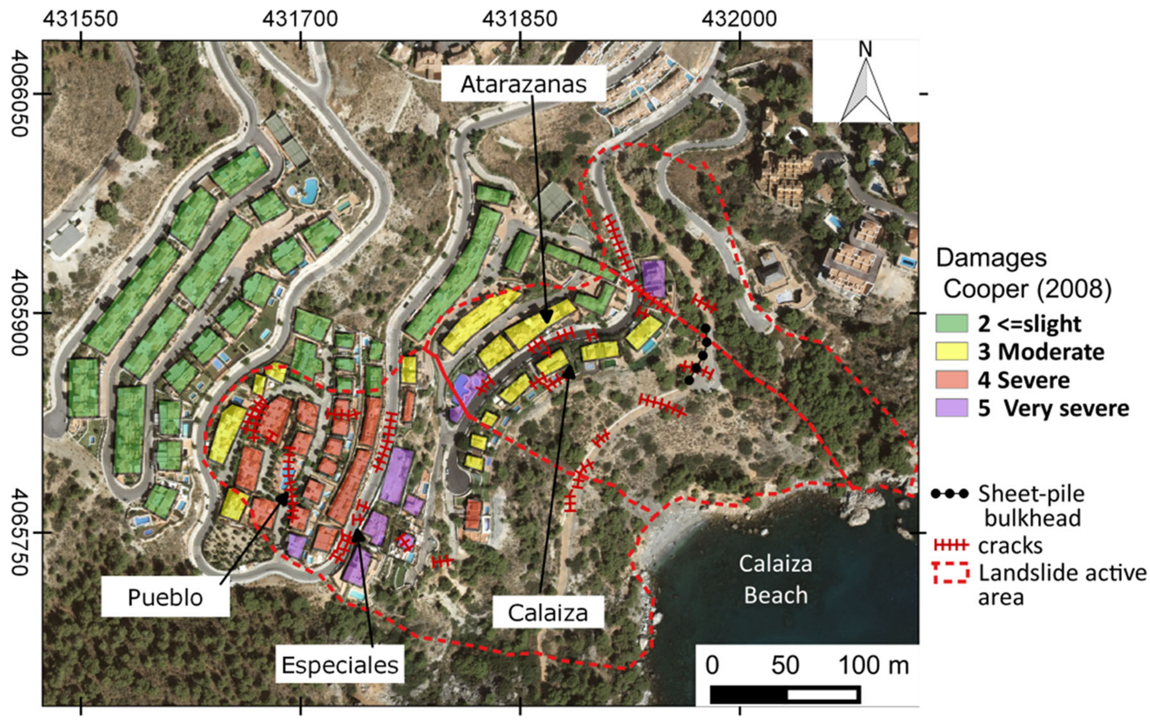

Fig. 4 Map of damage based on Cooper (2008) classification. Updated in January 2016

Fig. 5 Photos of damage. **a** Garden area of a house located in the NE extreme of Calaiza; **b** house in Pueblo with very severe damage; **c** detail of the interior of a house in Pueblo; **d** access road and retaining wall in Atarazanas; **c** access road in the Especiales site

until 2006, when the last dwellings in the resort were completed (Fig. 2). The resort is located on a steep coastal slope (35° on average) which is covered by scrub vegetation and pine trees. The area had to be terraced, and numerous earthmoving and fill-in works were carried out to level the land. The uppermost houses are located at an altitude of around 200 m and the urban development was extended downslope to an altitude of 50 m. The development consists of 416 luxury houses with two to three floors, many of them with private swimming pools (Fig. 2b). They are detached or terraced housing, the most recent dominating the seafront. Shallow foundations were used in all the houses, and especially spread-footing foundations. Some communal facilities (gardens, swimming pools, paddle courts) and access roads were also built. Eighty-five percent of the houses are used as holiday residences, and during the summer, a population of around 1500 people live in the resort, which is scarcely occupied during the winter season.

Damage survey

In 2006, cracks, open fractures, distorted windows and frames, and disrupted pipes started to appear in the "*Especiales*" housing development, and 2 years later, severe structural damage was observed, which led to the demolition of one of the houses (Ortega-Espinosa 2010). During the period 2007–2009, damage continued to appear in other parts of the resort, not only in the dwellings but also in the access roads, streets, walls, gardens, swimming pools and the electricity, gas, water and wastewater networks. A substantial amount of water recharged the slope during this time, due to leaks from pools and water supply pipes that went undetected for a long time. In 2008, the company decided to carry out repair and maintenance works, as well as new initiatives to determine the origin of the damage. The most relevant measure to mitigate slope movement was the construction of a 40-m long/44-m deep sheet-pile bulkhead wall on the lower part of the slope (Fig. 4); it is currently broken and tilted in some parts.

During the rainy winter of 2009–2010, there was a notable increase in the damage (Rodríguez-Ortiz 2011) which spread to other parts of the resort: the Pueblo, Atarazanas and Calaiza developments, where some homes had to be evacuated as well as in the Especiales development. The deterioration of the resort has worsened during the past 5 years and specifically during the later rainy winter 2012–2013: numerous dwellings require partial or complete rebuilding and new cracks have appeared in the access roads and retaining walls. In November 2015, the City Council officially declared a state of emergency in the area and a total of 24 dwellings have been evacuated. Great social alarm has been caused in the neighbourhoods as the evacuation is planned to be extended to 40 more dwellings in the coming months. Figure 5 shows some recently taken photos of the most damaged areas.

An inventory of damage was carried out in January 2016 (Fig. 4). The buildings were categorised following the classification proposed by Cooper (2008) according to different degrees of damage. The author rates the damage from 0 (no damage) to 7 (total collapse). The most affected areas are located in the lower part of the resort (*Pueblo*, *Especiales*, *Atarazanas* and *Calaiza*) where numerous houses and places have been assessed as having a level 4 degree of damage (severe) and some of them a level 5 (very severe). Based on the distribution of damage, the boundaries of the current active landslide area have been drawn, and three main bodies have been identified: the southwestern one, where the most severe damage has been detected (Pueblo and Especiales); the central body, with moderate damage to buildings (Atarazanas, Calaiza) but with open cracks on the lower part of the slope; and the north-eastern body, where very severe damage has been reported in two dwellings (already evacuated) and long cracks have been identified. There is a clear spatial correlation between the original landslide body identified in 1957 (Fig. 3) and the current active area.

Climate: damage triggered by rainfall

The SE coast of Spain has a typical Mediterranean climate. More specifically, the coastal fringe of the province of Granada has a genuine micro-climate, as the coastline is trapped between the Mediterranean Sea and the Sierra Nevada mountains (3479 m). Rain is very scarce (352 mm as an annual average) but heavy rains are common, with extreme values of up to 350 mm/24 h (rainfall recorded in 1973 in the area; Notti et al. 2015). The maximum precipitation takes place during the autumn and winter seasons, while late winter and spring are slightly drier. Summer is the driest period, with no rainfall at all during July and August. Regarding temperature, the coast of Granada is called the *Tropical Coast* because of its warm climate, with annual average temperatures of 18 °C.

Damage history in the resort seems to show a clear relationship between the most damaging events and water recharge episodes (rainy events and leaks from swimming pools and the water supply network). To prove this temporal connection, monthly rainfall data has been recorded by the nearest weather station (Cuevas de NerjaES77, AEMET-Spanish Meteorological Agency) for the period spanning from January 2003 to January 2016. Figure 6 represents the accumulated rainfall (3 months) for this period and the history of damage. We have considered the 3-month accumulated rainfall period as the rainy months in the region are November, December and January, and thus, we can represent their influence better. Figure 6 shows that 2009–2010 winter was extremely rainy in the region, when accumulated rainfall was almost twice the average value. The most severe and spreading damage was reported at this time, as also happened in the Marina del Este resort (Notti et al. 2015). Later, during the rainy winter 2012–2013, new damage appeared which led to the progressive deterioration of the resort until the current state of emergency.

Monitoring methods and results

Two techniques based on remote sensing have been applied to monitor the study area: DInSAR and photogrammetry. The combination of both procedures intends to identify and measure a wide range of displacement rates, from millimetre/year to metre/year, taking into account the damage observed in the resort and its evolution.

By PSInSAR

Landslides affecting urban areas are especially suitable to be identified by DInSAR, as buildings are very good SAR reflectors. Numerous works compare damage to buildings with InSAR-derived displacement data are becoming very frequent in the literature (e.g. Ferlisi et al. 2015; Bianchini et al. 2015; Ciampalini

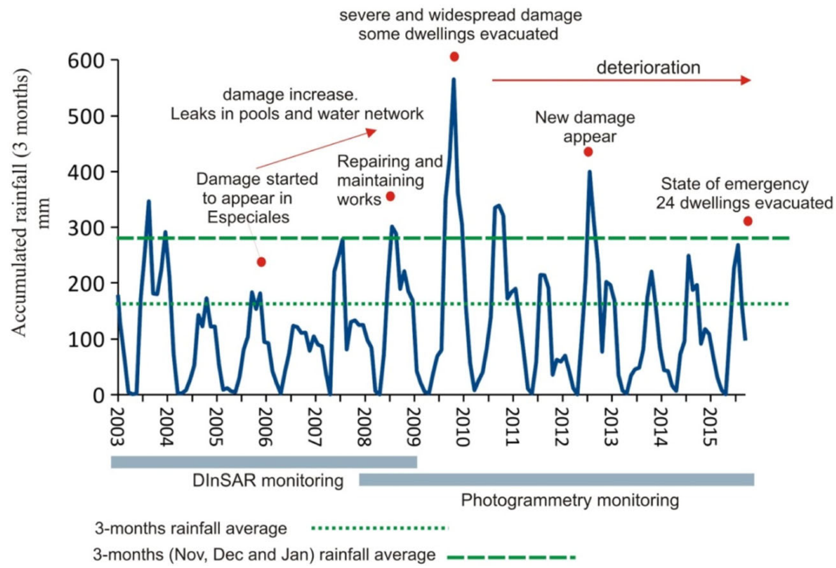

Fig. 6 Three-month accumulated rainfall for the period January 2003–January 2016 and the temporal representation of the main damage events. Two rainy winters (2009–2010 and 2012–2013) occurred and severe and new damage appeared. The monitoring periods have also been indicated

et al. 2014; Sanabria et al. 2014; Bru et al. 2013; Herrera et al. 2012, 2013; Cigna et al. 2010, 2013).

In the present work, a set of 25 ENVISAT SAR images acquired in ascending geometry during the period spanning from May 2003 to December 2009 was used. The deformation measurements were derived using the PSI approach described in Crosetto et al. (2011) and following the same procedure applied in Notti et al. (2015). The PSI processing allowed us to estimate the deformation over a set of 101 PS. Figure 7 shows the spatial distribution of the PS superimposed onto the damage map. Results show the confirmation of the stable areas and specifically those located uphill of the active landslide body. Nevertheless, in this "stable" area, a group

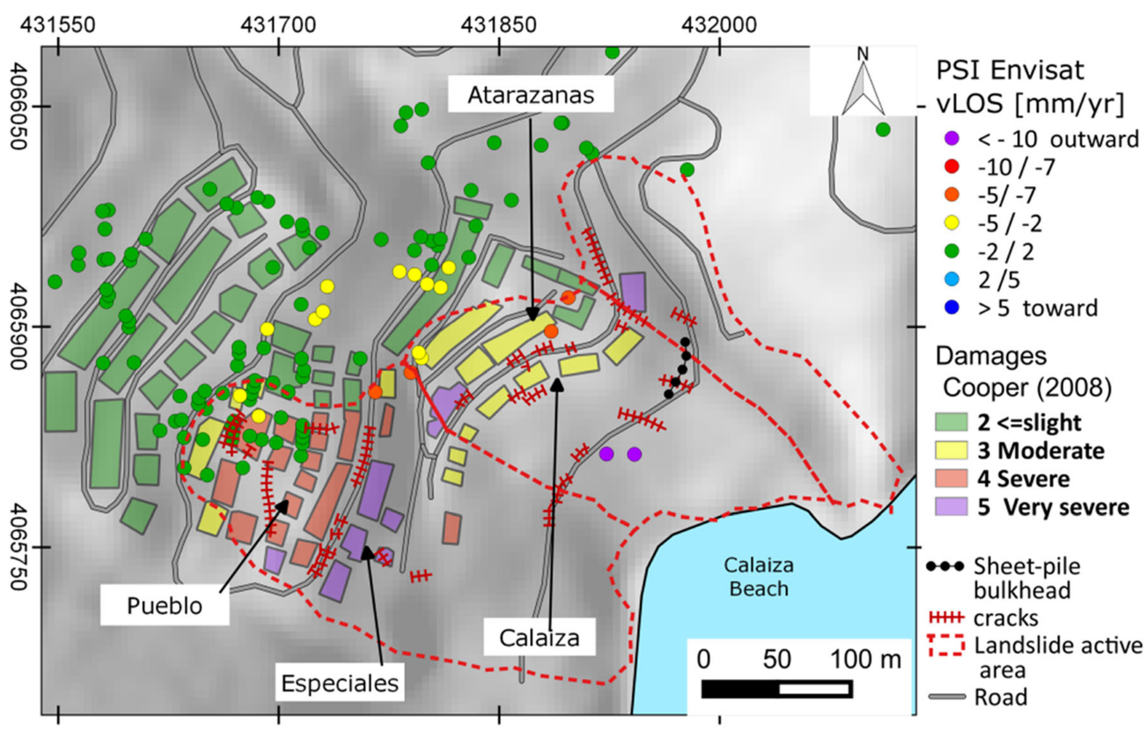

Fig. 7 PS velocity map based on ENVISAT ascending data (2003–2009) superimposed to the damage map. The stable area of the resort, located uphill of the active landslide body, is well characterised. Insufficient PS from the active landslide area have been obtained to monitor movement

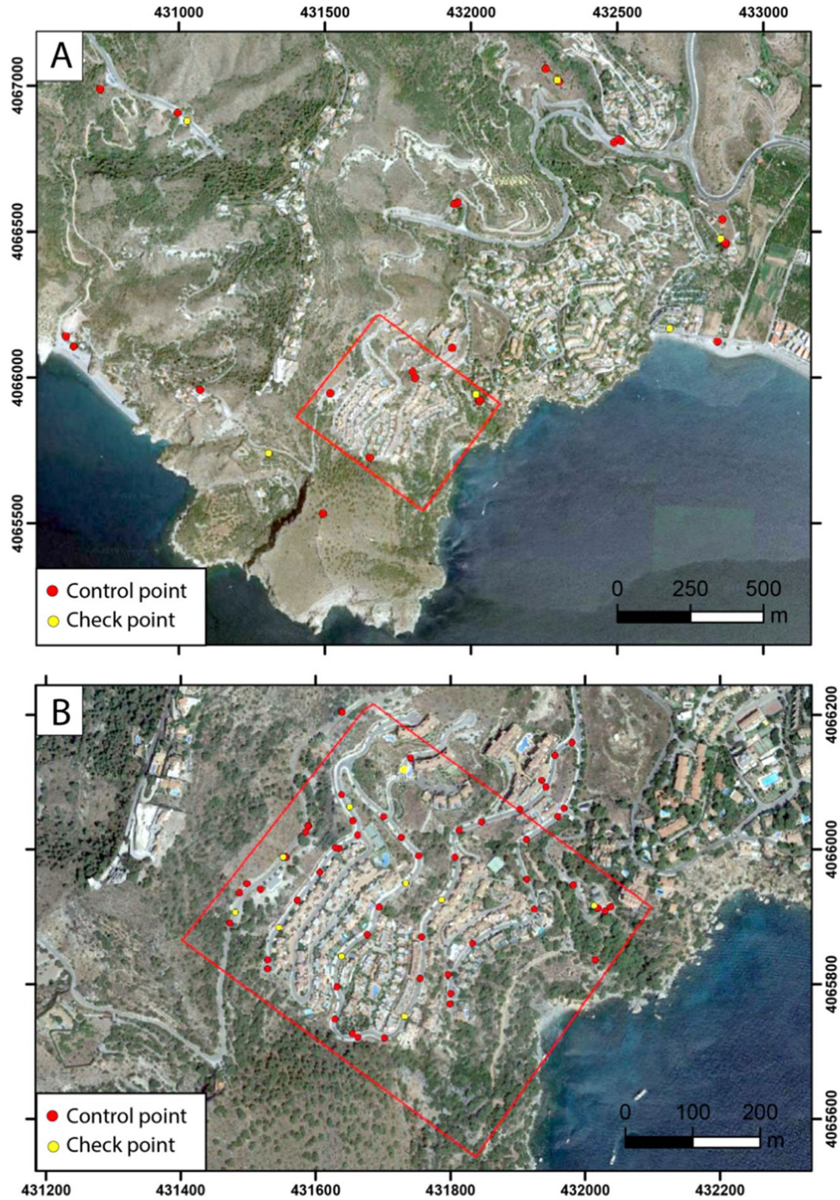

Fig. 8 *Upper image*, location of the 24 control points and the 6 check points used for the 2008 flight; *lower image*, location of the 52 control points and the 10 check points used for the 2015 and 2016 UAV-derived images

of PS with low velocities, between −2 mm and −5 mm/year, appear where no damage has been detected yet. Within the active landslide area, and specifically in Pueblo site, a concentration of stable PS can be seen despite the damage observed. That is because the monitoring period is before the rainy event 2009–2010 when damage began to be detected in this site. Additionally, a low density of deformation measurement points was obtained within the active area, although all of them show deformation velocities

Table 1 Flight specifications regarding control and check points and RMS errors

					RMS control points			RMS check points		
Flight	No. of photos	GSD	Control	Check	RMSx	RMSy	RMSz	RMSx	RMSy	RMSz
2008	4	0.20	24	6	0.024	0.031	0.011	0.087	0.219	0.292
2015	87	0.05	52	10	0.030	0.029	0.035	0.042	0.031	0.064
2016	87	0.05	52	10	0.033	0.030	0.037	0.039	0.045	0.059

Table 2 Details from the three flights used in the present research

Date	Type of flight	Camera	Ground sampling distance (m)
2008	Conventional	Digital DMC	0.20
26/06/2015	UAV	Sony NEX-5	0.05
22/01/2016	UAV	Sony NEX-5	0.05

over 5 mm/year. The highest values of velocity (> −10 mm/year) are located in the lower part of the landslide where large cracks have appeared. The lack of PS results may be due to not only the unfavourable orientation of the slope (NW-SE) but also to the presumable high velocity ratios of the movement (over 20 mm/year, the threshold estimated for ENVISAT), especially in the Especiales site, where severe damage had already been detected.

By photogrammetry

In the present research, three photogrammetric outputs were used, dated in 2008, 2015 and 2016. The first one (2008) consists of conventional aerial photographs from the Spanish Geographic Institute (IGN). This set was selected because (1) the flight was carried out before the rainy period 2009–2010, which caused spreading damage in the resort, and (2) the images have the highest available radiometric quality and spatial resolution. On June 26, 2015, a set of UAV-acquired photographs covering the whole resort was taken. The altitude attained above ground ranged between 100 and 120 m. The ground control points were defined first, before capturing digital images, and they were referenced to a guidance point located in the stable area, and later processed by applying Global Navigation Satellite System (GNSS) techniques. In addition to the control points, check points were also defined to check the quality of the image orientation (Fig. 8). Twenty-four control points and 6 check points were used for the 2008 flight, and 52 control points with 10 check points for the 2015 and 2016 UAV-derived images (Table 1, Fig. 8). RMS errors for both control and check points are presented in Table 2. Based on the ground control points, images can be well oriented. The same procedure was applied to acquire the UAV images in January 2016. Some additional details from the three flights used can be seen in Table 2.

The 2008 scenario was superseded by the 2015 UAV flight, which was considered the reference state. In the same way, the 2016 flight has recently provided updated information. The raw images were processed in order to create digital elevation models and orthophotos. 3D-building models were created based on view-stereo techniques for the different dates. Some buildings where photogrammetric restitution did not allow enough points to be gathered to extract an accurate 3D model were discarded (Dai et al. 2014). They are located in the upper sector of Atarazanas and the NE sector of Calaiza.

All the analysed buildings were characterised by averaging a mean displacement vector with all the individual vertex displacements between the 2008 and 2015 building footprints (Fig. 9). The individual displacement vectors were calculated taking the horizontal projections and the absolute distances for the 2008–2015 timespan. Averaged mean vectors were scaled to centimetre/year. This approximation evaluates each building as a displacement unit, thus avoiding small discrepancies between vertices from the same building footprint (Fig. 9).

Figure 9 shows an example of the stereo restitution carried out on a building displaying its position in 2008 and 2015. Based on this, and considering all the vertices of the building roof, the displacement vector for each vertex has been calculated. The displacement vector for the entire building is considered the average value of all of its vertices. Based on this, Fig. 10 has been created showing the total displacement vector obtained for each building located in the most damaged areas (with the exception of the indicated failed areas) for the eight monitoring years. We can observe that the largest displacements are recorded in the houses located in Especiales with values close to 2 m. In the SW part of Calaiza, the displacement values are between 0.75 and 1.25 m, and in Pueblo, the values range from 0.25 to 0.75 m. The direction that the vector shows is a very interesting data because it allows the landslide flanks as well as the three previously defined lobes

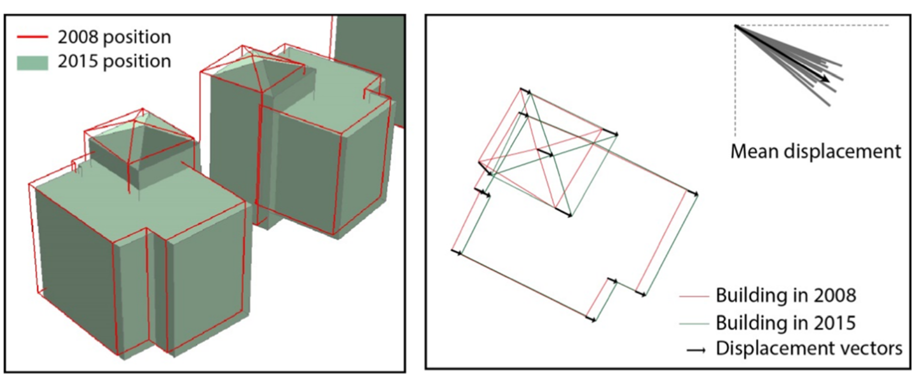

Fig. 9 Stereo restitution (3D) carried out on a building displaying its position in 2008 and 2015 (*left figure*). The *right figure* shows the way to calculate the average vector for each building, considering all the vertices of the roof. Based on this, displacement vectors of the buildings for the period spanning 2008–2015 have been calculated

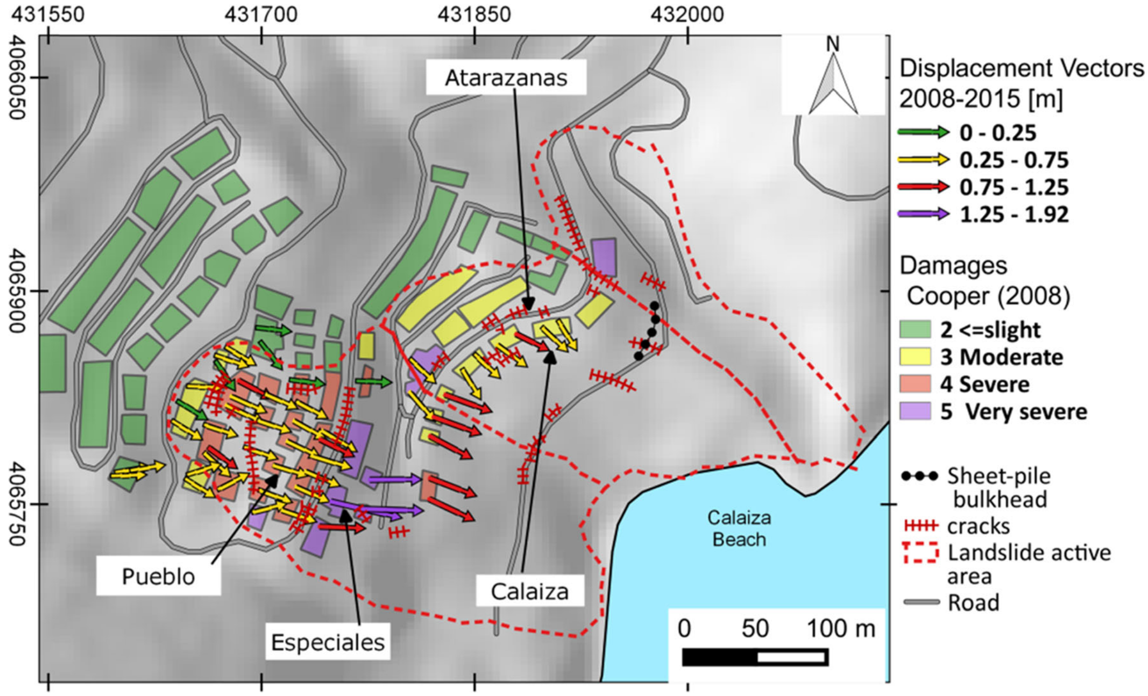

Fig. 10 Displacement vectors of the buildings for the period spanning 2008–2015 superimposed onto the damage inventory map. A general NW-SE direction of the movement can be observed, each vector allows the landslide flanks as well as the previously defined lobes, to be defined with accuracy. The southwestern sector of the resort is the most active and is where major building displacements (up to 1.92 m in 8 years) and the most severe damage have been detected

to be defined with accuracy. A general NW-SE direction of the movement can be observed.

No differences at all have been detected between the January 2016 UAV flight and the June 2015 flight. Thus, no displacements have been obtained over the confidence interval of the method (5 cm). In this sense, the 2008–2015 analysis shows the same results as those of 2008–2016.

Discussion and conclusions

The Cármenes del Mar resort can be considered one of the most extreme examples on the Mediterranean coast of Spain of severe pathologies associated with urban development on coastal landslides. Part of the resort was built on a deep-seated coastal landslide. Numerous earthmoving and fill-in works were carried out to level the steep land, and a considerable concentration of load was placed at the crown of the landslide; not only houses with two to three floors but also numerous swimming pools. The effects of all these changes on the land determined the activation of the landslide, and damage in the resort started to appear as soon as the last house was handed over.

In the present work, the use of PSInSAR and photogrammetry techniques (including UAV) has been combined. The monitoring covers the period from May 2003 to January 2016, the period in which damage has appeared in the resort. The combination of data from deformation measurements, damage observed and the geology of the site allows a better understanding of the landslide kinematics.

From the geological point of view, the landslide affects a highly tectonized and soft formation composed of dark graphite schists whose exfoliation tends to dip toward the slope. Furthermore, if we take into account the strength parameters obtained for this material, the slope is shown to have been approaching a rigorous limit-equilibrium before the resort was built. This fact was already considered in the report of Vorsevi (1998).

The history of damage reveals a clear relationship between the most damaging events and water recharge episodes, not only related to rainy periods (winters 2009–2010 and 2012–2013) but also related to leaks from swimming pools and the water supply network (2006–2008). Consequently, building damage is not homogeneous throughout the time. For this reason, building displacements have not been detected by means of UAV photogrammetry during the period from June 2015 to January 2016, as the region has experienced a dry autumn.

The monitoring carried out by applying PSInSAR techniques (2003–2009) reasserts the stable area at the top of the slope, where part of the resort was built over a hard substratum composed of marbles. The monitoring shows coherent PS in this stable area but not enough PS to evaluate the landslide activity in the damaged area. PSInSAR results show an area with no activity at the head of the landslide during the monitoring period but later damaged during the rainy period 2009–2010. It could be interpreted as the landslide-head retreating. On the other hand, some PS showing slight activity have been identified uphill of the landslide head, where no damage has been detected yet. This area located immediately north of Pueblo and Atarazanas could be a future, unstable area. At the moment, the uppermost limit of the active area is the contact between the marbles and the schists. We can conclude that there is a clear lithological control in the spatial distribution of damage and landslide activity.

The photogrammetry monitoring has allowed the quantifying of building displacements within the active body and the identification of the direction of the movement for each building. There is a general NW-SE displacement direction toward the sea, but some local lobes can be identified, the southern one being the most active with major building displacements (up to 1.92 m in 8 years) and the most severe damage detected (Fig. 10). This area was built on a colluvial and chaotic deposit which overlies the schist formation and is where different water levels were identified (Rodríguez-Ortiz 2011). Vertical infiltration and shallow water table accretion above a permeability contrast can generate shallow landslides in this area. Additionally, spatial and temporal variability of the near surface groundwater response to precipitation or water recharge implies consequences for slope stability which coincide with the history of damage reported in the Especiales and Pueblo sites.

In general, the flanks and toe areas of the original landslide are the most damaged, and are where higher displacement rates have been observed (Fig. 10). Ephemeral streams are located along the flanks of the landslide and fluvial erosion contributes to the instability of these areas. Additionally, marine erosion tends to steepen the front of the active toe, this area being one of the most rapidly evolving places in the landslide, where numerous cracks and shallow failures have appeared and where the highest values of Vslope have been detected. The push exerted by the material advancing from behind produces significant deformations and changes in the morphology of this sector and can explain the high displacement values (0.75–1.5 m) obtained in the southern sector of Calaiza (Fig. 10). Nevertheless, some of these houses located on the seafront, despite photogrammetry showing large displacements, only present moderate damage. They are terraced houses, not detached, and have probably moved as one unit. Conversely, a group of houses located in the central lobe, in the western extreme of Atarazanas, shows severe damage but the displacements obtained are in the mid-range (0.25–0.75 m). They are detached houses in a very step area, and they seem to have been affected by spatially heterogeneous deformations. Additionally, some houses located at both sides of Pueblo site, and outside the current landslide boundaries, show displacements (up to 0.75 m in 8 years) which could indicate a future expansion of the landslide body and the consequent emergence of new damage.

The final conclusion is that permission for construction and housing should not ever have been granted in Cerro Gordo. The Cármenes del Mar case study raises challenging issues about the appropriate choices for the planning of urban areas with this type of geohazard. In Spain, it is necessary to incorporate natural hazards into urban planning rigorously, including policies to predict, prepare for and prevent phenomena of this type. Results obtained in the present work can contribute to the design of the emergency evacuation safety plan in the resort.

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