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Monitoring soil creep landsliding in an urban area using persistent scatterer interferometry (El Papiol, Catalonia, Spain)

Abstract Soil creep is characterised by slow displacement, with depths of a few meters and loosely defined limits. Buildings and infrastructure located on slopes affected by such landslides may suffer significant damages if their foundations are poorly dimensioned. The presence of soil creep in urban areas makes it necessary to develop landslide activity maps, derive hazard maps, and implement risk management plans. Even though both geological and geomorphological analyses can provide basic information, it is often necessary to use additional techniques to obtain information about ground displacements. This paper proposes a method to derive a soil creep activity map using a multi-approach analysis based on geological, geomorphological, and persistent scatterer interferometry (PSI) data. PSI is a satellite-based technique to estimate land displacement velocity. The work described in this paper was carried out in the town of El Papiol, in the metropolitan area of Barcelona (Spain). This is an urban area that has been heavily affected by soil creep over the past decades. The results achieved show that PSI data substantially improve the information provided by the geological and geomorphological analyses and make it possible to accurately define the landslide area and estimate its activity.

Keywords Remote sensing · SAR · Displacements · Creep · Activity map · El Papiol

Introduction

The objective of this paper is to assess the activity of shallow landslides in an urban area using a multi-approach analysis based on geological, geomorphological and persistent scatterer interferometry (PSI) data. Creep soil landslides are usually characterised by loosely defined limits, which makes them difficult to detect. If countermeasures are not taken, constructions and infrastructure built on these landslides can suffer damage over time. This paper is focused on the shallow landslide area of El Papiol, a town of 4000 inhabitants located 20 km from Barcelona.

The historical centre of El Papiol is located on the upper part of a hill (Figs. 1 and 2). Starting in the 1960s and up to the present, the town has undergone major urbanistic growth, multiplying its population by a factor of 4. During this period, the urban expansion affected the slopes of the hills that were previously covered by agricultural fields. In the 1970s and 1980s, following periods of heavy rainfall, the first cracks attributable to terrain instability appeared in the buildings located on the slopes, while no significant damages were recorded in the town's historical centre.

The major damages occurred in 1983 (Bordonau and Vilaplana 1987), when building displacements of up to several meters were recorded. As of that period, several buildings were restored and some were evacuated. Starting in the mid-1980s the El Papiol municipal government took measures to reduce the displacement

rates. Additionally, the construction of new buildings was not allowed in the area affected by major displacements. This corresponds to the Parc Central shown in Fig. 1.

The instability mechanism of El Papiol is due to soil creep (Hung et al. 2014; Bordonau and Vilaplana 1987). It affects the most superficial part of the terrain and is typically characterised by very slow displacements, from mm/year up to 0.1 m/year (Highland and Bobrowsky 2008). Buildings and infrastructure located on soil creep can show cracks, curved walls, etc. Over time, these can worsen, affecting the structural stability and, therefore, the functionality of buildings and infrastructure. In this context, it is useful to identify and map the buildings and infrastructure that are affected by terrain instability. This includes the structures with obvious damages, those that have been repaired and the ones that are undamaged because their structures have so far absorbed the terrain displacements. Geomorphology can provide a useful tool for this purpose. However, this cannot be used regularly in urban areas, where human activity often erases the geomorphological features caused by superficial landslides, e.g. terrain cracks, small lobes, curved scars, tilted trees, etc. For this reason, the use of complementary methods can be useful: in this study, the information provided by the PSI technique is described and discussed.

PSI is a radar remote sensing technique to monitor displacements that can be used to measure a wide range of deformation phenomena (Hanssen 2001; Crosetto et al. 2010, 2016). As for landslide monitoring, there are several PSI works that cover broad areas; see Righini et al. (2012), Strozzi et al. (2013) and Wasowski and Bovenga (2014). In addition, there are several studies focused on single large landslides; see Fruneau et al. (1996), Colesanti et al. (2003), Hilley et al. (2004), Crosetto et al. (2013) and Tofani et al. (2014). Most of these studies focus on displacements of large landslides for which previous geomorphologic analyses are available. As mentioned above, the challenge of analysing urban areas like El Papiol is that the boundary of the area affected by soil creep cannot be defined using geomorphologic criteria alone. Similar examples are described in Bovenga et al. (2013), Cigna et al. (2013), Wasowski and Bovenga (2014), Peduto et al. (2016) and Gullà et al. (2017). An advantage of PSI is its high sensitivity to small displacements, which allows us to detect extremely slow landslides, characterised by displacement rates of a few mm/year. This high displacement sensitivity is fundamental for an early detection of terrain displacements, even before they cause damages to buildings and infrastructure. This is especially useful to implement risk mitigation strategies. Other interesting features are the broad area coverage (e.g. over 1000 km² using very high-resolution TerraSAR-X or CosmoSkyMed data) and the remote sensing nature of displacement measurements. Last, another important advantage of PSI is the availability of archived SAR images of the area of interest. One limitation of PSI is its need for good reflectors in

Fig. 1 Orthoimage of the study area. The topography contour lines are expressed in meters above sea level. Source: Cartographic and Geological Institute of Catalonia. The yellow symbols indicate the viewpoints of the pictures from Fig. 2

the area of interest. This is usually guaranteed over urban areas, where manmade objects respond well to the radar microwaves, while it is not true for vegetated areas. Another limitation is the magnitude of the measurable displacements. This limitation, which is due to the ambiguous nature of PSI observations, depends on the spatial pattern of the displacement, the density of the measured points and the temporal SAR sampling (see Crosetto et al. (2016)). However, this limitation does not affect relatively slow displacement phenomena, like the one discussed in this paper.

Study area

Geographical and climatic background

El Papiol municipality has an area of 8.83 km². The historical centre, which includes a twelfth century castle, is located on the upper part of a hill (see Figs. 1 and 2). The absence of significant cracks in the historical building bears witness to the stability of this area. Urbanisation of the southern slope of the hill began in the 1960s. This development slowed down with the appearance of cracks in the buildings, especially in the areas characterised by the steepest slopes. At the bottom of the slope runs Les Argiles creek (“argiles” is a Catalan word for “clays”), where several small clay quarries were located in the past. The El Papiol area includes another hill called Les Escletxes, a Catalan term that means “cracks.” The name refers to the meter-wide cracks that show the limestone layer located at the top of the hill.

According to the Catalan Meteorological Service (Meteocat), El Papiol is located in an area with a Mediterranean climate, which is characterised by warm summers and mild winters, with maximum

rainfall during the autumn, dry summers and an average total annual rainfall of about 600 mm.

Geomorphological and geological frames

El Papiol lies in the geologic unit of the Vallès-Penedès graben, dating from the Miocene Epoch and oriented from NW to SE. More specifically, it is located in the eastern part of this graben, close to the Miocene normal faults that generated it—and that are nowadays inactive—in the study area. The Collserola hills, made by Palaeozoic materials, lie to the east, and the Llobregat River valley to the south.

Based on existing geological maps (Cirès and Berastegui 2012a, b) and in situ observations, the geology of El Papiol can be summarised by the following geological formations, ordered from the oldest to the newest (see Figs. 3, 4 and 5).

- The Basement (A) is represented by metasedimentary rocks from Palaeozoic ages. It appears in the lowest topographic parts of the study area.
- Red detrital materials from the Miocene Epoch (B). These materials lie directly above the basement with an approximate thickness of 50 m; they constitute a large part of El Papiol Hill. They include two distinct units: the upper one is formed by breccia, conglomerates and sandstones, while the lower one is formed by sandstones and mudstones. They have medium to low consolidation and can be easily altered. On the surface they show an alteration with a maximum depth of 5 m, which generates a cohesive terrain with a high clay content that is the cause of El Papiol’s instability.

Fig. 2 General view of the study area. C castle, E buildings built in the 60s and 70s; P: Parc Central; S: sport centre area; I: slopes affected by soil creep; A: Les Argiles creek; E: “Les Escletxes” area

- Miocene limestone (C). They are fossiliferous limestones of good hardness that are karstified. They have a thickness of 20 m and are slightly inclined towards the west. They outcrop in the highest parts of the study area: the Castle and Les Escletxes. At Les Escletxes the limestone layer has meter-wide cracks (Fig. 4) that indicate the instability of the underlying mudstones (B formation).
- Pliocene mudstones and sandstones (D). These are massive mudstones rich in carbonate, which have very low hardness and low consolidation. They have a surface weathering that is about 3 m thick, resulting in a cohesive mudstone soil. They outcrop in most of the slopes of the study area with highly variable thickness, and cover the rest of the oldest formations. The maximum thickness of about 20 m is reached at Les Argiles creek.
- Superficial formation from Early Quaternary (E). This comprises blocks, gravels, sands and mudstones with a low degree

of consolidation, located at the top of the El Papiol Hill. The lithologies of these pebbles are derived from the erosion of the Collserola hills. The weathering of this superficial formation leads to a granular soil with little cohesiveness. It has a thickness of approximately 10 m with a base located at an altitude of approximately 120 m.

Terrain instability

The terrain instability affects the first 5 m of B formation and possibly the D formation (Vilaplana and Bordonau 1984), at the most. There is no historical evidence of the historical centre, including the castle, having suffered significant damages due to slope instability. The oldest evidence of instability is given by the cracks of the C formation at Les Escletxes. The limestone dips 10° towards the SW. The origin of the cracks could be attributed to a

- Inactive very old planar slide. Exact boundary unknown. Thick lines are indicating the open old cracks and arrows the slope dipping.
- Approximate outline of the area affected by soil creep instability on 1983 according to Bordonau and Vilaplana (1987) by observing instability witnesses on the field. Arrows are indicating slope dipping.
- Approximate outline of the area affected by instability on 1971 according to the technical report by Fayas (1972).
- Rotational slide triggered on the beginning of 1983 according to Vilaplana and Bordonau (1984).
- Area affected by water erosion with prevalence of small gullies.
- Damages on buildings and ground pavements observed in the field trip done in years 2010 and 2012.
- Slight cracks are represented by red circles and bigger cracks and tilted structures by bold red circles.

Fig. 3 Geologic scheme of the area of interest in El Papiol simplified from Cirès and Berastegui (2012a and b) and historical instability. A: Palaeozoic basement; B: Miocene clays, mudstones, sandstones and conglomerates; C: Miocene limestones; D: Pliocene mudstones and sandstones; E: gravels, sands and mud from the Early Quaternary. Cross sections of this study area (I-I' and II-II') are shown in Fig. 5

planar sliding mechanism produced between the C and B formations. A comparison of aerial images from 1946 to 2013 shows that the distribution of cracks remained unchanged over these decades. Therefore, according to the classification by Cooper (2007), this can be considered a dormant slide.

Heavy rains fell in September 1962, causing catastrophic floods in the lower Llobregat Valley, with a maximum intensity of 250 mm of precipitation falling in 6 h (Barrera et al. 2006). Despite these rains, there is no record of the El Papiol area suffering damages due to ground displacement. This could be explained by the fact that at the

Fig. 4 Outcrop of residual materials from the Miocene (formation B) remobilised by the soil creep; photo taken from “Les Escletxes” (upper left). Detail of the Miocene limestones (formation C) affected by a crack with an opening of about 5 m; Photo taken at “Les Escletxes” (upper right). Outcrop of residual materials from Pliocene (formation D) remobilized by the soil creep; Photo taken from the foot of El Papiol Hill (bottom left). Outcrop of Quaternary detrital materials (formation E) remobilized by the instability; photo taken at the top of El Papiol Hill (bottom right)

time the town was confined to the historical centre and did not occupy the slopes susceptible to instability.

The urban area expanded quickly in the 1970s and 1980s. The first damages to houses began on the southern slope of El Papiol Hill due to the rains that fell in late 1971. The heavy rainfall caused instability in the urban area located above the current location of the Parc Central. The instability completely ruptured the sewer network, triggering leaks into the subsoil (Bordonau and Vilaplana 1987). An increase in the instability took place in November 1983, generating the most important damages (see Figs. 6 and 7). In March 1984, a new acceleration occurred that caused still further damage. Measures were taken at that time to reduce displacement rates and control urban expansion. Since then no remarkable displacement episodes have been registered, neither during the heavy rains of October 1987 nor those of June 2000 (Llasat et al. 2003). The terrain instability continues today, but without causing the damages of the 1970s and 1980s. The sector that has suffered the most damage is the urban green area known as Parc Central (Figs. 1 and 2), where infrastructure is often damaged, requiring continuous repairs.

The exact extent of the terrain instability—extremely slow today—is unknown. In fact, the official 1:5000 geological maps (Cirès and Berastegui 2012a, b) neither indicate the terrain instability nor define the extent of the slope instability surface in this sector.

PSI data processing and analysis

The PSI data processing and analysis over the El Papiol area were carried out using the PSIG approach described in Devanthery et al.

(2014). It was based on 42 ascending StripMap TerraSAR-X SAR images that cover the period from December 2007 to June 2012. The images are uniformly distributed over the observation period; they have perpendicular baselines that range from -333 to $+506$ m. The main PSI processing steps are concisely described below (see Devanthery et al. (2014) for detail).

1. Selection of the candidate persistent scatterers (PSs), which in this approach are named cousin PSs (CPSs). This was accomplished by using a set of seed PSs and searching for their “cousins”, i.e. PSs with similar characteristics.
2. 2D phase unwrapping was performed on the candidate CPSs using a redundant set of interferograms. In this case, 633 interferograms were used. This was followed by a phase unwrapping consistency check to select the final set of CPSs.
3. Using the selected CPSs, the atmospheric phase screen (APS) was estimated using spatio-temporal filters and then removed from the original interferograms.
4. The estimation of the displacement velocity and the residual topographic error (RTE) over a dense set of PSs was performed using a denser set of PSs.
5. The RTE phase component was removed from the wrapped APS-free interferograms.
6. A 2+1D phase unwrapping was finally executed on the set of APS- and RTE-free interferograms to obtain the displacement velocity map and time series.

The displacement velocity map of the El Papiol area is shown in Fig. 8. The estimated velocity values are superposed to a SAR

CROSS-SECTION I-I' (NW-SE) : EL PAPIOL URBAN AREA

CROSS-SECTION II-II' (SW-NE) : "LES ESCLETXES" URBAN AREA

Fig. 5 Cross section I-I', which concerns El Papiol Hill, and cross-section II-II', of "Les Escletxes" Hill. The location of the profiles is shown in Fig. 3. A, B, C, D and E refer to the formations described in the "Geomorphological and geological frames" section

amplitude image of the area. These values refer to the line-of-sight (LOS) direction of the radar, i.e. they represent the displacement

component along the direction that connects the satellite and the area of interest. The displacement velocity map in Fig. 8 contains

Fig. 6 Building damaged by the reactivation in autumn 1983, located downslope from the Parc Central area (image courtesy of Dr. Jaume Bordonau) (a). Photo of the inside of an evacuated building located on "Les Escletxes" Hill (b)

Fig. 7 Damages to a building located on El Papiol Hill (a, b). Crack in the road located above the Parc Central, where damages occur continuously (c)

approximately 4400 measured points or PSs. Most of the PSs are green, showing that the area is globally stable. However, there are two sectors that show displacement. The first one, which appears in yellow, shows positive velocity values that stand for displacements away from the satellite. By contrast, the second one, which appears with blue colours, shows negative values, i.e. displacements towards the satellite. We assume that both displacements are downward and approximately parallel to the local slope. They

are seen from the radar with opposite values due to the different geometry of the two slopes with respect to the LOS (see Fig. 9). The along-slope projection is discussed in Colesanti and Wasowski (2006) and Cascini et al. (2010). Figure 9 shows the map of cumulative displacements over the entire observed period (from December 2007 to October 2012). In this case, the values were projected in the direction of the steepest slope. The displacement time series are discussed later in this paper.

Fig. 8 LOS displacement velocity map of the study area (period of observation: 2007–2012). This figure approximately covers the same area shown in Fig. 9

Fig. 9 Cumulative displacement map of the study area obtained from PSI (period of observation: 2007–2012). The LOS displacement was projected along the steepest slope direction. The white box in the bottom right part of the figure illustrates the LOS components of two identical displacement D of two slopes, one bent away from the ascending satellite S (the case of El Papiol Hill, left) and the other one facing S (the case of “Les Escletxes” Hill, right). In the first case, the LOS displacement D_{LOS} is positive (in yellow), while in the second case, it is negative (in blue). This occurs in the two sectors shown in Fig. 8

Fig. 10 Times series showing the temporal evolution of displacements on the seven sectors selected (from B to G in Fig. 9). The displacement is projected on the direction of the steepest slope direction

Fig. 11 Displacement time series (represented by lines) versus precipitation. The upper plot represents the sector B located on El Papiol Hill, the middle one represents the sector C in the Parc Central area, and the lower one represents sectors E, F and G on Les Escletxes Hill. In all plots, each bar represents 1 month. Bars in dark blue represent the maximum rainfall received in 1 day on a monthly basis, while the bars in light blue represent the total monthly rainfall

Analysis of the results

Magnitude of the terrain instability

Figure 9 shows displacements in El Papiol and Les Escletxes hills. Between these two hills there is a slope that includes the Parc Central area. It is worth recalling that the PSs basically cover the built-up areas, whereas in the areas of vegetation, there are no PSs. Based on the results shown in Fig. 9, the following interpretation of terrain stability was derived. Most of the PSs are green, indicating zero or negligible displacements (below 10 mm in the 5-year observed period). The PSs that show displacement are concentrated on the slopes that belong to the Les Argiles Creek basin.

There are some isolated orange or red PSs in the green zones, some of them located in flat areas. It must be borne in mind that isolated displacements may not be due to terrain instability, but

rather to very local displacements of light poles, other metallic elements, or single buildings. Seven main sectors have been identified in the displacement-affected zones (see Fig. 9).

- Sector A: Aligned houses of the same street located on El Papiol Hill. The PSs, with displacements up to 50 mm, are located in a rather flat area over houses built in the same period. There is no evidence of instability resulting from the 1971 or 1983 episodes. After an in situ observation, the displacement of this sector was judged to be due to causes other than soil creep, e.g. the differential settlements due to problems related to building foundations. For this reason, this sector was not further considered in this work.
- Sector B: Buildings located on El Papiol Hill, with displacements ranging from 20 to 40 mm, belonging to the Les Argiles

watershed. This sector suffered displacements in 1983. Some damage is still visible (Fig. 7a, b).

- Sector C: Street located above of the Parc Central, where a large crack (Fig. 7c) can be observed. This sector coincides with a sliding area that occurred during the 1971 and 1983 episodes. Its displacements range from 50 to 80 mm.
- Sector D: Set of buildings located below Parc Central. The major damages occurred in this sector in 1983 (Fig. 6a). The displacements range from 15 to 150 mm.
- Sector E: Damaged buildings on Les Escletxes Hill, some of which have been evacuated (Fig. 6b). This sector was urbanised after 1983, and therefore, there are no historical damage records. The displacements range from 20 to 40 mm.
- Sector F: Football pitch retaining wall, showing some pathologies. This sector was urbanised after 1983. The displacements range from 40 to 100 mm.
- Sector G: New houses located above the football pitch, which show no pathologies. This sector, which was urbanised after 1983, has displacements between 30 and 70 mm.

Figure 10 shows the displacement time series estimated using PSI over the above sectors. The time series refer to single PSs located in each sector. The time series of Sector A show displacements up to 80 mm. However, in this sector, the ratio between the displacements projected parallel to the local slope and the original LOS values is 19: this amplification factor makes the values of the time series unreliable; see Colesanti and Wasowski (2006), Cascini et al. (2010) and Plank et al. (2010). For this reason, the time series for sector A are not shown in Fig. 10. Sectors B, E, F and G show displacements with similar magnitudes over time. Sector C shows three types of displacements over time: an initial period with a moderate downward displacement rate, followed by a second period with no apparent displacement, and a final period with a slow upward displacement. This could be related to the different stabilisation works of the road retaining wall. Sector D shows the biggest displacements. In general, the displacements of the time series are not continuous: they are irregular, mainly due to the noise and atmospheric component of the PSI observations (Crosetto et al. 2016).

In order to analyse the above displacements in detail, three main groups (El Papiol Hill, Parc Central and Les Escletxes Hill) were plotted in Fig. 11. The above figure, which corresponds to sector B, shows cumulative displacements of about 50 mm and two patterns: from 0 to 385 days, there is a moderate displacement rate, while in the second period observed, the rate is higher and rather constant. Note that the time series show some spikes, which are probably due to residual atmospheric effects. The middle figure (sector D) displays a cumulative displacement of 200 mm and a pattern similar to the previous figure: a moderate displacement rate between 0 and 385, followed by a period with a higher displacement rate. The figure below shows a cumulative displacement of up to 100 mm, which has a rather constant rate over the entire observed period.

Precipitation and instability acceleration

For superficial landslides, activation (or acceleration) may depend on surface water due to rain, rather than the piezometric groundwater level. To assess the effect of heavy rain on the activity of El

Papiol soil creep, the displacement time series were compared with the rainfall records. Using the data published by the Catalan Meteorological Service (www.meteo.cat), recorded at the weather station in Castellbisbal (located about 5 km from El Papiol), two variables were considered: the cumulative monthly rainfall and the maximum daily rainfall on a monthly basis (see Fig. 11). The maximum registered values are about 200 mm/month and 160 mm/day. One may notice that the displacement rates are not correlated with the cumulative monthly rainfall or the maximum daily rainfall per month.

It is worth comparing the rainfall records of 2007–2012 with those from 1971 and 1983. This is useful to analyse the effectiveness of the measures taken from administrations to cope with the damaging instability. Unfortunately, the Castellbisbal weather station began keeping its records in 1983. Therefore, we used the nearest available station with rainfall records starting in 1924, located at the Barcelona Airport, about 12 km away from El Papiol, which is managed by the Spanish Weather Agency (www.aemet.es). Since 1924, the highest daily rainfall in December corresponds to December 5, 1971, with 106 mm/day, while the highest monthly rainfall occurred in December 1971 with 312 mm/month. Considering the month of November, the highest daily rainfall was on November 7, 1983, with 101.7 mm/day, and the highest monthly rainfall was in November 1983, with 356.3 mm/month. Therefore, considering the entire recorded period, both December 1971 and November 1983 rainfall events represent extreme episodes. The total rainfall of these events was sufficient to trigger or accelerate the instability. By contrast, the rainfall registered in the 2007–2012 period was insufficient to activate the instability.

Landslide activity

A spatial analysis of instability was performed using geomorphological and geological information, historical records and the PSI data. The procedure involved two stages. In the first one, the unstable areas were identified, while in the second one, these areas were classified according to their activity. The unstable zones correspond to areas where the underlying geology and the topography make them prone to instability in the form of soil creep. This information was compared with the results from PSI. The detrital material from Miocene, Pliocene and Quaternary (formations B, D and E) was considered to be potentially favourable to cause instability. In fact, the alteration of these materials gives rise to a superficial formation that becomes unstable. From the areas with the above materials, we discarded those that show morphological traces associated with stability, e.g. gullies. The Les Escletxes zone was added to the potentially unstable areas due to the wide cracks of this area. All remaining parts of the areas were considered stable.

The classification of the unstable zones was done according to Cooper (2007), using four classes: active, dormant, stabilised and relict (see Table 1 and Fig. 12).

The active zones were considered to be those where the cumulative displacements observed by PSI are above 10 mm (i.e. over 2 mm/year in the observed 5-year period). Given the wide range of observed displacements, the active zones were divided in two subclasses: very active, with cumulative displacements of over 25 mm (Ac in Fig. 12), and moderately active, with cumulative displacements between 10 and 25 mm (Am in Fig. 12). Most of the

Table 1 Classification of the shallow landslide activity from the geomorphological witnesses, geology, instability historical record and PSI results

Shallow landslides activity	Geomorphological witnesses about major landslides	Instable geological substratum	Historical events on instability	Cumulated displacement detected by PSI from 2007 to 2012 (mm)
Very active	Not	Yes	Either yes or not	> 25
Moderately active	Not	Yes	Either yes or not	(> 10, < 25)
Dormant	Not	Yes	Yes	Negligible (< 10)
Stabilised	Not	Yes	Yes	Negligible (< 10)
Relict (only large landslide)	Yes	Yes	Not	Negligible (< 10)
Stable	Not	Not	Not	Negligible (< 10)

damaged buildings belong to subclass Ac. It is worth mentioning that the active zones detected by PSI include those affected by the rainfall episodes of 1971 and 1983, according to the technical reports (Vilaplana and Bordonau 1984; Fayas 1972).

The unstable areas classified as dormant (Dm in Fig. 12) are those that were active during the episodes of 1971 and 1983 according to technical reports, but proved to be stable according to the PSI analysis between 2007 and 2012. It is worth mentioning that

Fig. 12 Landslide activity map according to the classification by Cooper (2007) obtained from (a) geomorphological evidence found in the studied area, (b) historical instability records, (c) PSI results and (d) geological information

the top of the dormant area, located on the slope of Les Escletxes Hill (G in Fig. 9), has localised cumulative displacements of about 25 mm. This could be a residual displacement of the dormant area that coincides with a large building or could be due to poor foundations of the same building.

The unstable areas classified as stabilised (Sd in Fig. 12) are the ones that were active during the episodes of 1971 and 1983 but have no displacements detected by the 2007–2012 PSI analysis, and where the administration has taken measures to stabilise the terrain.

Finally, relict activity is the result of instability that occurred in the geological past, proven by large, ancient cracks, when the climatic or orographic conditions were different. This is the case of the planar slide of Les Escletxes Hill, which was not activated in 1971 and 1983, and shows no displacements in the PSI analysis.

Discussion

The landslide activity map shown in Fig. 12 was derived using a multi-approach analysis based on geological, geomorphological, historical and PSI data. The novelty of this work is the application of PSI data in the analysis of a shallow landslide in an urban context. The most important points of this work are briefly discussed below. The first one concerns the utility of the displacements estimated by PSI to derive the landslide activity map. Without these displacements, it would have only been possible to use the historical data on the episodes of 1971 and 1983, and the inventory of damaged buildings (see Fig. 3). In this way, an active zone with very imprecise limits would have been identified. Even worse, it would have been smaller than the area mapped using the PSI results. In this context, the PSI analysis proved useful to study the activity of a shallow landslide in an urban area (see Peduto et al. (2016) and Gullà et al. (2017)). The second point concerns the technique to monitor displacements. The landslide activity mapping requires a complete monitoring of the urban area at hand, especially when no geomorphological features are available to guide the mapping. The use of conventional techniques (extensometers, inclinometers, etc.) seems inadequate to monitor entire urban areas, both in terms of logistics and costs. Assuming that enough SAR images of the area of interest are available in the archives, PSI offers the important advantages of monitoring historical displacement with a wide area coverage capability. The conventional techniques could be used to derive more detailed studies. It should be noted that PSI has several limitations. The first is the SAR data availability, which is markedly uneven around the globe. The second is the impossibility to get PSI displacement measurements over vegetated areas. A further potential limitation is the cost of the SAR images. The very high-resolution imagery by TerraSAR-X (used in this work) and CosmoSkyMed is quite expensive. By contrast, the medium resolution imagery of Sentinel-1 is free of charge. There are important quality differences among the PSI products. The LOS velocity map (see Fig. 8) has a precision of the order of 1 mm/year (see Crosetto et al. (2016)). The transformation from the LOS values into displacements parallel to the slope involves the multiplication by a factor, which amplifies the errors; see Cascini et al. (2010), Bovenga et al. (2013) and Wasowski and Bovenga (2014). Finally, the displacement time series are usually noisier than the velocity maps: the single LOS displacement

values can have error values of several millimetres. These errors are amplified when the LOS values are transformed in displacements parallel to the slope, as in Fig. 9.

The utility of the derived landslide activity map is worth evaluating. The active zone includes three types of buildings: damaged, repaired after damage, and undamaged. The identification of the active zone (Ac and Am in Fig. 12) could help the administration to focus the activities meant to reduce the instability. As an example, these could include the control of the leaks of sewer and water supply networks, reinforcing the foundations of the most vulnerable buildings and stabilising the largest walls. The map identifies the areas where the stabilisation measures have been efficient (Sd in Fig. 12). In addition, the map identifies the zone where more exhaustive monitoring is needed (Dm in Fig. 12). In general, the map provides valuable information to support risk management related to shallow landslides. We must underline that this map lacks information for the nonurbanised areas, as a consequence of the aforementioned PSI limitation. This limitation could be overcome using conventional techniques or performing PSI using corner reflectors (see Crosetto et al. (2013)).

Conclusions

Soil creep can cause severe damages to buildings and infrastructure and even affect urbanistic development if appropriate measures are not taken. To manage the associated risk, it is necessary to map the affected areas and estimate the landslide activity. The use of traditional techniques, such as “in situ” and aerial imagery observations, is suitable for medium and large landslides that feature large landforms that are often easy to identify. However, these traditional techniques are insufficient to achieve an accurate identification of the areas affected by small landslides like soil creep. In fact, the shallow depth and the slow displacements of these small landslides make small and smooth landforms in clayey soils. These small landforms are highly erodible, which makes their identification by geomorphological criteria difficult. This is even more challenging when buildings and infrastructure eliminate any geomorphological evidence of instability.

The test area for this work is El Papiol, a town highly affected by soil creep. A traditional work procedure based on geological observation, building damage mapping and geomorphological terrain analysis, yielded an incomplete and inaccurate soil creep inventory map (Fig. 3). For this reason, we planned to use the PSI technique in order to analyse the terrain instability using 42 StripMap TerraSAR-X SAR images that cover the period from December 2007 to June 2012. The PSI results identified a larger unstable area which completed the soil creep inventory map and provided information to perform more accurate boundaries of the affected areas. Using the PSI results we were able to draw up a soil creep activity map considering fundamental information useful to perform hazard maps in a subsequent work. Hazard maps are tools used by the stakeholders to manage the risks associated with terrain instability. The landslide activity map follows the classification by Cooper (2007), based on the type of activity: active (ongoing displacements), dormant (past displacements, now apparently stable, with no correcting measures), stabilised (past displacements stabilised by correcting measures), relict (no displacements, but with evidence of instability in the geological past) and stable (no displacements, now or in the past). The active class includes a wide range of displacements. For this reason, two sub-

classes were proposed: moderately active and very active. The landslide activity map was complemented by the PSI displacement time-series, which describe the displacement temporal evolution.

Collecting spatially detailed information on the instability activity is a necessary condition to accurately map terrain instability and its activity, which in turn are keys to manage the associated risk. In situ measurements, as inclinometers and extensometers, involve high costs in order to achieve a spatially detailed description of displacements. PSI was crucial to improve inventory map and perform the activity map. An advantage of PSI is its ability to measure “back into the past”, provided that SAR images of the area of interest are available in the archives. To conclude, PSI analysis is a useful technique, to be used together with geological and geomorphological processes, to derive landslide activity maps and manage the risk associated with soil creep.

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