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MULTI-SCALE OBSERVATION AND MONITORING OF RAILWAY INFRASTRUCTURE THREATS

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Automatic classification of Active Deformation Areas

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Acronyms and Abbreviations

ADA	Active Deformation Area
DAM	Deformation Activity Map
MI	Match Index
PS	Persistent Scatterer

Automatic classification of Active Deformation Areas

1 Executive Summary

The aim of this task is to develop a methodology to use ADA maps from the railway corridor as inputs in order to perform an automatic pre-classification of the polygons according to the different possible geological or geotechnical hazards. The proposed method checks the possibility of each previously identify ADA to be a certain type of geological or geotechnical hazard providing complementary "quality" information to support the preclassification process.

2 Introduction

Barra et al [RD1] developed a procedure to periodically and automatically update and assess the activity of areas affected by geohazards by taking advantage of the wide area coverage and the high coherence and temporal sampling of the new generation of SAR satellites (Figure 2-1).

The main products derived from the developed methodology consist on the deformation activity map (DAM) and the active deformation areas map (ADA). This second map provides a quick view of the most reliable active deformation areas.

ADA maps represent polygons grouping clusters of five or more active contiguous persistent scatterers (PS)(Figure 2-1). For each cluster, the number of PS, the mean, maximum and minimum as well as some quality indexes are calculated.

In this document, a methodology to classify the recognized active areas of deformation (ADA) is exposed in detail (Figure 2-1).

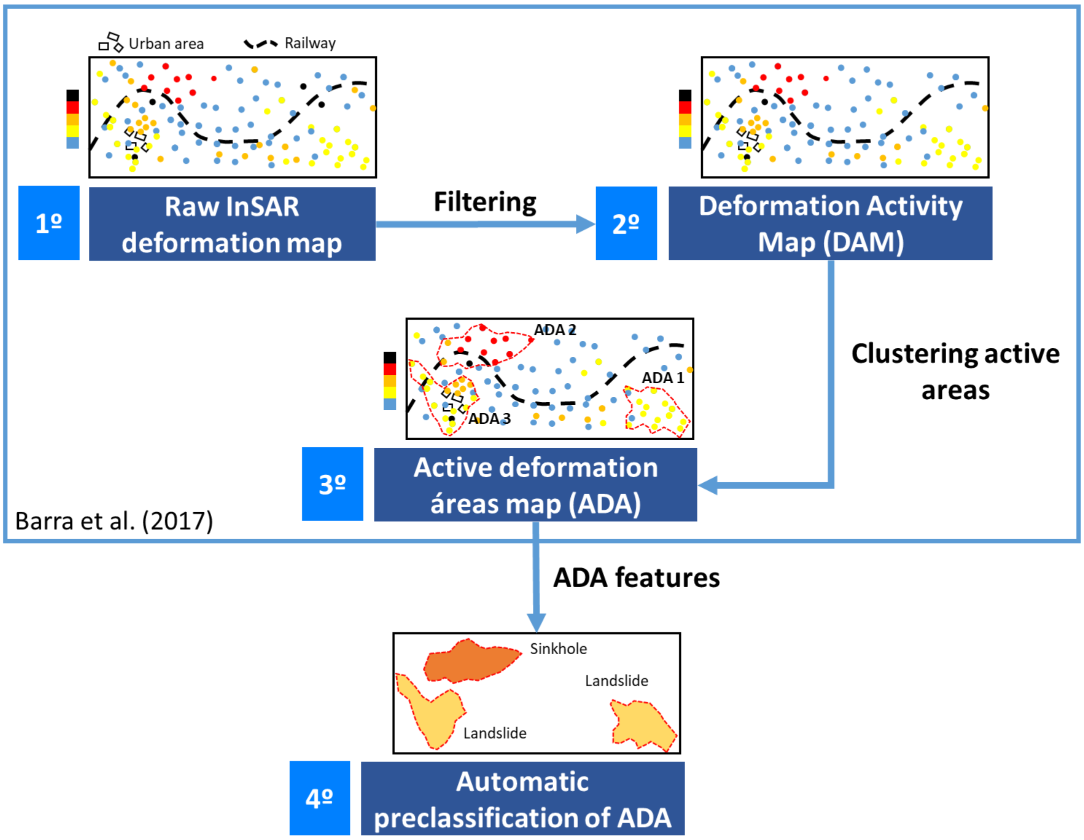


Figure 2-1 – Workflow for the preclassification of ADA.

3 Geological and geotechnical hazards

The first step to develop the abovementioned procedure for the automatic preclassification (or pre-screening) of the ADAs consists on the identification of the different hazards that could affect the railway infrastructures and their nearby areas. Only those natural hazards that can be detected by means of space-born InSAR are considered in this procedure.

These hazards can be divided into six groups (Table 2-1):

- Landslide
- Sinkhole (only pre-failure displacements)
- Land subsidence
- Constructive settlements
- Expansive soils
- Temperature effects

Although thermal effect is not strictly a geological or geotechnical risk, it has been also considered in the analysis in order to be differenced from other seasonal displacements as those related with expansive soils that can also affect infrastructures.

Note that earthquakes have been excluded from the list of considered hazards since the displacements associated to this type of phenomena are sudden and, therefore, their effect on the railway infrastructures cannot be monitored along time by means of PS time series.

Collapsible soils also suffer a quick deformational process, which cannot be measured by InSAR and thus have not be considered in this document.

Each one of these hazards present their own characteristics as well as specific properties (e.g. the type of lithology in which they develop or their velocity trend). Consequently, these particular features (Table 2-1) can be considered for a pre-screening of the detected ADA as will be explained in detail in next sections.

The velocity (i.e. the deformation rate of a PS for a certain time-period) is a parameter that considerably varies for the different processes and even within the different parts of a certain process. For example, the velocity of landslides can vary from "extremely slow" (lower than 16 mm/year) up to "extremely rapid" (> 5 m/s) and within a landslide different velocities can be measured depending on the considered part of the landslide [RD2]. Therefore, the velocity on its own is a difficult parameter to be used to discriminate different geological and geotechnical processes of the clusters. However, certain processes present characteristic deformation trends that can be exploited for the identification of the process. For example, a consolidation settlement of an embankment or a foundation presents a characteristic time-settlement curve in which velocity gradually reduces along time (negative exponential). Similarly, thermal processes and expansive soils show seasonal patterns of deformation along time in which velocity cyclically increases and decreases. It is worth noting that InSAR presents some limitations to measure fast deformation processes and therefore, depending of the wavelength of the sensor, fast PS cannot be measured (e.g. usually, displacements higher than

>1600 mm/year cannot be monitored with spaceborn InSAR, [RD3]).The sign of the displacements also can be used to distinguish certain processes. In a cluster placed on a landslide, positive and negative velocity values can be found depending on the geometry of the satellite system and the ground surface. Constructive settlements and the precursor deformations of sinkholes are always negative. Finally, expansive soils and deformations associated to thermal effects can alternate positive and negative values.

Total magnitude of the displacements of the cluster areas (i.e. accumulated displacements for a determined period) can be also used to discriminate some processes. For example, the deformations produced by thermal effect are usually very small. However, in a landslide the distribution of accumulated settlements can considerably change within the unstable area).

Ground slope is a parameter widely used for discriminating areas prone to landslides from those in which landslides cannot develop. Although some type of landslides can develop even on very smooth reliefs (e.g. earth flows) the ground surface slope can be considered to discard the occurrence of this type of phenomena on those areas with a slope lower than 10º. Other processes such as land subsidence, usually occur on flat areas (fluvial plains) and thus, can be discarded on areas presenting high slopes. The other processes numbered in Table 2-1 can develops under different relief conditions and then this parameter cannot be used for discriminating them.

Some processes develop under certain conditions and scenarios, exhibiting a high correlation with external parameters. Next are some of the relationships between certain factors and the displacements measured by InSAR: a) The activity of landslides, land subsidence due to water withdrawal and sinkholes is usually related with piezometric levels of groundwater. b) Geology is also a typical conditioning factor: Sinkholes only develop on saline or carbonate lithologies, land subsidence occurs over Quaternary unconsolidated fine deposits (mainly Holocene deposits) and expansive soils develop on certain type of lithologies (e.g. certain type of marls, clays, etc.). c) Constructive settlements and thermal deformations affect infrastructures and therefore the clusters associated to this processes are always placed over infrastructures. d) Thermal displacements are closely related with temperature time-series.

Summarizing, the automatic classification of the processes underlying the ADAs detected by InSAR is very complex due to the high variety of parameters and factors associated as well as the heterogeneous behaviour that these processes exhibit. However, a tentative preliminary automatic classification of the processes can be made based on the above-described features.

ID	Process	Size of the cluster	Velocity	Velocity sign[b]	Horizontal displacement[d]	Total magnitude	Ground[c] slope	Correlated with	Observations
1	Landslide	Local (usually < hundreds of m^2)	Up to 5 m/s	+/- depending of the InSAR acquisition and slope geometry	Very high	From mm to m	>10º	▪ Piezometric levels ▪ Geology	▪ >1600 mm/year cannot be monitored with spacecraft InSAR. ▪ Inventory maps can be used for classifying these features.
2	Sinkhole	Local (usually < hundreds of m^2)	Prefailure - <100 mm/year Failure - instantaneous	Negative -	Not	From mm to cm (during prefailure) and m (during failure)	Not correlated with slope	▪ Piezometric level ▪ Geology (carbonatic rocks and saline rocks)	▪ Inventory maps can be used for classifying these features. ▪ InSAR only allows to measure prefailure deformations (precursors).
3	Land subsidence	Regional (tens or hundreds of km^2)	<110 mm/year[a]	-/+ (predominantly negative although may be positive in some periods)	Not or very low	From mm to m	<10º (flat areas of valleys)	▪ Piezometric levels ▪ Unconsolidated sediments (Quaternary)	
4	Constructive settlements (Consolidation settlements)	Local (located over infrastructures)	Variable along time (velocity gradually reduces along time according to pore pressure dissipation)	Negative -	Not or negligible	From mm to cm	Variable (over infrastructures)	▪ Infrastructures location and constructions	
5	Expansive soils	Local	General trend of time series is equal to 0. Positive and negative velocity can be found.	+/- depending of the moisture content (clear seasonal trend)	Not or negligible	mm	Not correlated with slope	▪ Geology ▪ Rainfall or groundwater table	Clear seasonal trend.
6	Temperature effects	Local (located over infrastructures)	General trend of time series is equal to 0. Positive and negative velocity can be found.	+/- depending of the temperature magnitude (clear seasonal trend)	Not or very low	mm	Variable (over infrastructures)	▪ Temperature ▪ Infrastructures location	▪ Clear seasonal trend.

Table 3-1 – Summary of the general deformational properties and characteristics of the different geological/geotechnical processes that can affect railway infrastructures regarding their possible identification by means of InSAR technique. a. This reference magnitude corresponds to the case study exhibiting maximum land subsidence due to water withdrawal in Europe is the Guadalentin Valley. b. Negative values (-) indicate sinking and positive values (+) uplift. c. Although some landslides can develop with slopes lower than 10º (e.g. earth flows) we have adopted this criteria that is based on most of the landsliding processes. d. Horizontal displacements can be available when ascending and descending orbits are processed in InSAR.

4 Automatic preliminary classification of ADAs

4.1 Classification of ADAs

As it has been mentioned in the previous section, unfortunately, not-unequivocal parameters of features can be used to identify the different processes of deformation of the ADA. In other words, different geological and geotechnical processes can exhibit similar deformation properties and similar features.

Consequently, the proposed procedure will be focused on the evaluation of the possibility that a certain ADA can be affected by a process. Therefore, for each ADA we will evaluate if the underlying process is compatible with a landslide, a sinkhole, land subsidence, etc. only discarding those processes that we are sure, according to the available information, that cannot be concurring on the analysed ADA. In other words, an ADA could be pre-classified as different processes (e.g. a landslide, sinkhole and constructive settlement) at the same time if the parameters of the ADA fit the features of these processes.

It is worth noting that an automatic and accurate procedure for classifying the processes based on the deformational information of the ADA is not possible only using InSAR information, although the proposed procedure will give us the opportunity to state possible processes associated to the measured displacements. However, later human supervision and interpretation of the ADA, jointly with other tasks (e.g. fieldwork or photointerpretation) would allow refining the classification process.

The proposed procedure will perform for each ADA a series of tests in order to state the compatibility of the measured deformations with the typical features of each process.

The input data will consist on:

- a database with the n Active Deformation Areas (ADA) and their quality indexes derived from the procedure defined by Barra et al (2017).
- a geological map (polygons)
- a vector map of the railway infrastructures (polygons).
- a landslide inventory map (polygons)
- a sinkhole inventory map (polygons)
- a land subsidence inventory map (polygons)
- a expansive soils map (polygons).
- a DEM model

When some of these data are not available for the area under study, the pre-screening process will be performed applying other complementary analysis included in the prescreening chain.

Then, once n ADAs have been identify from the InSAR raw data, for each cluster i (ADAi), from i=1 to n, a series of conditions (Table 4-1) will be evaluated and consequently, the potentially of each cluster to be classified as a certain type of geological/geotechnical process will be considered.

ID type 1 (Landslide)					
Does the ADA_i match the inventory map?	Yes	**Landslide**			
	No	Slope > 10º	Horizontal displacem.?	Yes	**Potential new landslide**
			Horizontal displacem.?	No	**Not a landslide**
		Slope < 10º	**Not a landslide**		

ID type 2 (Sinkhole)					
Does the ADA_i match the inventory map?	Yes	**Sinkhole**			
	No	Saline or carbonate rock/soil	Horizontal displacem.?	Yes	**Not a sinkhole**
			Horizontal displacem.?	No	**Potential new sinkhole**
		Other lithologies	**Not a sinkhole**		

ID type 3 (Land subsidence)					
Does the ADA_i match the inventory map?	Yes	**Land subsidence**			
	No	Quaternary unconsolidated sediments?	Yes	Slope >10º	**Not land subsidence**
				Slope <10º	**Possible land subsidence**
			No	**Not land subsidence**	

ID type 4 (Constructive settlements – consolidation settlements)				
Is the whole ADA_i placed within the infrastructures (building, embankment, bridge, etc.) area?	No	**Not constructive settlements**		
	Yes	Does the time series fit a exponential function?[a]	Yes	**Consolidation process.**
			No	**Not consolidation process**

ID type 5 (Expansive soils)				
Is the ADA_i placed within an area of potentially expansive lithologies (geology map)?	No	**Not expansive soils**		
	Yes	Does the time series fit a sinusoidal function?[b]	No	**Not expansive soils**
			Yes	**Potential expansive soil**

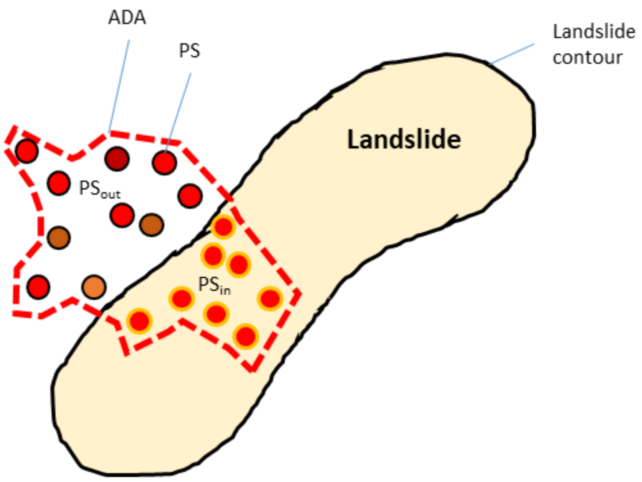
ID type 6 (Temperature effects)				
Is the whole ADA_i placed within the infrastructures (building, embankment, bridge, etc.) area?	No	**Not expansive soils**		
	Yes	Does the time series fit a sinusoidal function?[b]	No	**Not thermal effects**
			Yes	**Potential temperature effects**

Table 4-1 – Pre-screening conditions to be implemented into a GIS for the automatic pre-screening of the deformational processes affecting the ADAs. a. Primary consolidation follows a curve similar to a negative exponential. Therefore, the function to be fitted will be $\delta = A + e^{(-B\cdot t)}$. B. The function to be fitted will be $\delta = A \cdot sin\left(\left(\frac{2\pi}{T}\right)\cdot t + \emptyset\right)$ and the considered periods (T) will be 1 year and 6 months for time series of, at least 1 year.

4.2 Match index and correlation coefficient

Note that most of the relationships used during the pre-screening procedure analyse the spatial coincidence of the cluster of PS (i.e. the ADA) with the mapped areas (e.g. the contour of a landslide). However, sometimes this match can be only partial, i.e. only a part of the ADA is within the contour of the mapped geological/geotechnical process. This fact can be due to: a) errors inherent to the InSAR method or the mapping processes (e.g. inaccuracy in the delineation of the processes or the geocoding of the PS). b) the lack of updating of the inventory maps (e.g. a new landslide can develop or subsidence con enlarge the sinking area).

Therefore, in this method we propose to calculate the Match Index (MI) that indicates the percentage (%) of PS from the ADA that are within the previous mapped geological/geotechnical process (Figure 2).



$$Match\ Index = \frac{nº\ PS_{in}}{nº\ PS_{in} + nº\ PS_{out}} \times 100$$

Figure 4-1 – Description of the Match Index (MI).

In general, high values of the Match index indicate a good coincidence of both, the area of the mapped process and the PS cluster (i.e. the ADA). In those cases in which MI=100% there is a maximum coincidence, i.e. the whole cluster is within the contour of the mapped area. On the contrary, in those cases in which MI is equal to 0, the coincidence is null.

On the other hand, most of the analysis implies the fitting of a function. In those cases in which a fitting process is performed the maximum, minimum and mean correlation coefficient (more specifically the well-known Pearson's correlation) will be provided as a quality index for each ADA.

5 Conclusions and Recommendations

This document presents the guidelines for the automatic pre-screening of the Active Deformation Areas (ADA) identified from InSAR data. Due to the complexity of the different involved geological and geotechnical processes the proposed procedure is based on a series of typical characteristics of the considered processes that allow to check if certain conditions concur and then to attribute or discard the possibility of occurrence of this process.

Parent Documents

The parent documents establish the criteria and technical basis for the existence of this document.

[PD1] Shift2Rail Joint Undertaking (S2R JU) – Multi-Annual Action Plan (MAAP) – Rev. 3 – 26/11/2015

[PD2] Shift2Rail Joint Undertaking (S2R JU) – Annual Work Plan 2017 – Version 1.1- 23/12/2016

[PD3] MOMIT – Description of Action (DoA) – GA 777630

Reference Documents

Reference documents are those documents that, although not a part of this document, serve to amplify or clarify its contents, or dictate work policy or procedures.

[RD1] Barra, A., Solari, L., Béjar-Pizarro, M., Monserrat, O., Bianchini, S., Herrera, G., Crosetto, M., Sarro, R., González-Alonso, E., Mateos, R., Ligüerzana, S., López, C. & Moretti, S. 2017. A Methodology to Detect and Update Active Deformation Areas Based on Sentinel-1 SAR Images. Remote Sensing, 9, 1002.

[RD2] Cruden, D.M. & Varnes, D.J. 1996. Landslide types and processes. In: Turner, A.K. & Schuster, R.L. (eds.) Landslides: investigation and mitigation (Special Report). National Research Council, Transportation and Research Board Special Report, Washington, DC, USA, 36–75.

[RD3] Metternicht, G., Hurni, L. & Gogu, R. 2005. Remote sensing of landslides: An analysis of the potential contribution to geo-spatial systems for hazard assessment in mountainous environments. Remote Sensing of Environment, 98, 284-303, doi: http://dx.doi.org/10.1016/j.rse.2005.08.004.

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