ABSTRACT

Most of the urban areas located in the lacustrine or fluvio-lacustrine depressions of the central sector of the Mexican Volcanic Belt (MVB), such as Morelia, Celaya, Aguascalientes, Salamanca and Querétaro, during the last two decades registered differential ground subsidence. To understand this phenomenon and to identify the main causes that generate it, geological investigations were carried out using different methodologies. The results of the investigations have related the ground settlements to the over-exploitation of groundwater resources that, generating a decrease of the pore water pressure in the solid phase of the soil, causes the consolidation of the lacustrine and fluviolacustrine sediments. The combination of groundwater withdrawal with the presence of regional and local systems of normal faults have been addressed as the controlling factors of the identified ground settlements. Indeed, the main damaged buildings and structures have been detected along preferential directions which are parallel to the regional fault system. In this paper we present the preliminary results of an InSAR analysis carried out over the main cities of the MVB, some of which are included in the UNESCO World Heritage List. The analysis aimed at detecting the spatial patterns and the annual rates of subsidence, as well as to identify periods in which land subsidence has been intensified by the conjugation of other phenomena such as "La Niña", a meteorological phenomenon that caused a drought period. To achieve these objectives, we used ENVISAT SAR data spanning the period 2003-2006, acquired within an ESA Cat-1 project. The analysis revealed the presence of ground displacements along the linear structures identified in the field, reaching velocities up to 5-6 cm/year. To improve the understanding of the on-going phenomena, the displacement maps provided by the InSAR processing have been analyzed along with ancillary data, such as piezometric maps, geologic maps, and validated with the available in-situ measurements. The InSAR analysis confirmed how the tectonic structures of the MVB control the ground settlements. Furthermore, the obtained deformation maps enabled to extend the mapping of the main faults even over urban areas not yet identified by field surveys, due to the still scarce superficial evidences.

1 INTRODUCTION

Since the 1980s, habitants of some cities built-up in lacustrine or fluviolacustrine depressions of the central sector of the Mexican Volcanic Belt (MVB), a complex volcanogenetic zone E-W oriented, some 20-200 km wide and 1,000 km long; started to notice that their houses, pavements of the streets, pipelines and railways were affected by differential ground settlements oriented along preferential directions [1]; [2]; [3]; [4]. The most important cases of urban areas affected by ground settlements are represented by Morelia, Celaya, Querétaro, Salamanca, Aguascalientes, etc., some of which, namely Morelia and Querétaro, have been included in the UNESCO World Heritage List thanks to their historical and cultural relevance.

In order to understand the origin of this phenomenon and to address the main causes that generate it, geophysical and geological investigations were carried out in the last years using different methodologies. In the City of Morelia researchers from the Michoacana University, through the advice of geotechnical, paleosesimological and geophysical investigations, concluded that the ground instability can be explained by land subsidence induced by groundwater overexploitation, but with the peculiarity to be structurally-driven. In fact, the main ground deformations are located along preferential directions which are parallel to the regional faults systems. Based on the elements necessary for the generation of such a phenomenon they refer to it as Process of Subsidence-Creep-Fault (PSCF) [4]. In fact, the elements involved are land subsidence connected to the withdrawal of the aquifer systems that generates a decrease of the pore water pressure in the solid phase of the soil, causing the consolidation of the lacustrine and fluviolacustrine sediments; creep to denote that this type of deformation is slow, continuous through time and aseismic; and the presence of tectonic structures such as geologic faults buried by lacustrine and fluviolacustrine sediments. Indeed, the presence of pre-existing sub-surface discontinuities, such as faults, within or below the aquifer system can lead to differential vertical compaction in the case of groundwater withdrawal due to different factors, mainly referred to differences in the thickness of compressible materials which compose the
aquifer, differential water level declines across the discontinuities and lateral variations in the compressibility of the aquifer materials.

Despite the existence of several detailed studies focused on the analysis of the causes and extension of ground settlements in some specific cities or portions of cities located in the central sector of the MVB [4]; [5]; [6] there is a lack in the knowledge of the spatial extension and on the temporal evolution of such a phenomenon over the whole central MVB. For this reason, within the framework of a joint initiative of the Michoacana University and the University of Firenze, a DInSAR analysis of Envisat data acquired over the area of interest have been carried out. To achieve these objectives, ENVISAT SAR data spanning the period 2003-2006 were acquired within an ESA Cat-1 project. The analysis aimed at detecting the spatial patterns and the annual rates of subsidence, as well as to identify periods in which land subsidence has been intensified by the conjugation of other phenomena such as "La Niña", a meteorological phenomenon that caused a drought period.

In the following sections the geological features of the cities preliminarily analyzed in the first part of the current research, the characteristics of the acquired Envisat images and the processing carried out are summarized, followed by a discussion of the results for everyone of the analyzed cities and the description of the work still in progress.

2. STUDIED AREA

The cities in the central portion of the Mexican Volcanic Belt (MVB) affected by Processes of Subsidence-Creep-Fault (PSCF) are settled upon ancient lacustrine or fluviolacustrine depressions that were active until the Upper Pleistocene. These depressions are in general valleys associated to the course of the Lerma River or its tributaries. The cracking’s cities of Morelia, Querétaro and Celaya are presented in this paper (Fig.1), the first city is affected by a NE-SW faulting system, typical of the MVB, while the other two cities are encompassed by a NNW-SSE faulting.

The city of Morelia is settled on a zone of strong influence from two different geological domains: to the south, the Sierra de Mil Cumbres or Santa María Region, presenting a sequence of vulcanite outcrops made up of lavas, breccias and pyroclasts of andesitic composition, which have been placed in the Middle Miocene (12 My). Above this sequence, and in the absence of paleosoils, a sequence of ignimbrite named “Cantera de Morelia” is present, with a variable thickness ranging from 10 to 120 m. Overlying the ignimbrite a lacustrine, eventually becoming fluvial, sequence is present having a thickness of about 60 m and ages from the Miocene (8 My) to the Pleistocene. At the top of this terrigenous sequence outcrop the volcanic products of the volcanoes Quinceo, Las Tetillas and Cerro del Águila, which are lava flows, breccias and pyroclasts of basaltic or andesitic composition. All the above described units appear affected by NE-SW and E-W faults. The urban area of Morelia is strongly affected by the superficial effects of such a fault system, with morphological evidences consisting of 1 m-high scarps in some part of the city. The most important faults affected by differential settlements are represented by the Central Camioniera cracking and the La Colina cracking.

Figure 1: Location map of the MVB (Mexico). Orange dots represent the cities investigated in this study.

The city of Querétaro is located in a larger horst and graben area delimited by NNW and ENE oriented faults. The intersection of these faults created the Queretaro graben, a composed tectonic structure delimited by two NW faults, the Oriente and the San Bartolomé Faults. More locally the main faults N-S oriented that delimit a smaller graben are the 5 de Febrero fault to the East of the city and the Tlacote fault to the West of Queretaro. The graben is filled with sequences of andesitic lavas and basalt masses of Miocene-Pliocene ages and tuffs covered by granular material of fluvial or lacustrine origin. Groundwater resources in the Querétaro area have been strongly exploited in the last 20 years, with common depletion rates of the water table around 3 m/year and a maximum decrease of the water level in the central part of the valley of 160 m [7]. The most important fault in relation to the PSCF is represented by the 5 de Febrero cracking. The first cracks were noticed in the early 1970s and by the beginning of the 1980s the cracks evolved in a faulting [6]. Currently the superficial evidence of such a movements consists of a fault scarp with a vertical offset of more than 1 m at some locations along its trace [5].
The city of Celaya is located on a large alluvial and fluviolacustrine plain resting upon a basement of Cretaceous rocks of volcanic and sedimentary origin that outcrops in the Sierra de Guanajuato. From the base to top three sequences can be recognized: a sequence of pyroclastic and terrigenous layers with a depth of over 50 m; an alternation of andesitic and basaltic lava flows measuring from a few meters to over 300 m in depth, with associated pyroclastic products and a granular sequence from the Pliocene-Pleistocene made up of an alternation of clays, sands, conglomerates and pyroclastic products with thicknesses from a few meters to 200 m. Within this sequence, several levels of clays are embedded forming the main aquitards. The cracking associated with PSCF in Celaya has a NNW-SSE direction. Damage has been registered in the downtown area with elevation changes starting from the 1980s of more than 2 meters along the main fault system.

3. THE INSAR ANALYSIS

For the detection and measurement of ground movements a conventional DInSAR analysis was carried out using data acquired by Envisat satellite between 2003 and 2006. In order to limit the effect of temporal and spatial de-correlation of the InSAR signal the selection of the suitable data pairs within the ESA archives has been driven by the cross check on perpendicular baseline vs. time interval. The selected dataset, consisting of 10 scenes, span the time interval from July 2003 up to February 2006.

Different effects reduced, up to compromise in some cases, the quality of the interferometric analyses. First of all, temporal de-correlation of the signal induced by the variations of the dielectric properties of the targets between the two acquisitions. Vegetated areas, due to the seasonal growth, caused significant phase de-correlation of C-band SAR couples over periods longer than few months, while urban areas, exposed rocks and man-made structures maintained high levels of coherence over longer time intervals. In addition, spatial de-correlation induced by the acquisition geometry, limited the applicability of InSAR to short baseline interferograms (up to 300-400 m).

Among all possible suitable combinations of interferometric pairs, as reported in Tab.1, high coherence over the urban areas has been preserved only on interferograms, with a maximum spanning interval of 490 days. Strong atmospheric artefacts affecting the interferometric phase have been noted on interferograms spanning the rainfall season and for this reason they have been excluded in such an analysis. For the other suitable pairs the particular pattern of the measured signal and its presence on multiple independent observations suggested a low impact of the atmosphere on the retrieved deformations, at least for the summer and winter couples.

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Tab.1: SAR couples used for the DInSAR analysis.

Considering the average values of the phase standard deviation over the surrounding stable areas allows an estimation of the accuracy in the displacement measurement of about 7-8 mm. The coherent pairs have been processed trough the “two pass interferometry” method in order to obtain the displacement component of the interferometric phase. The topography phase contribution has been eliminated by creating a synthetic interferogram containing only the topographic term of the phase from a pre-existing DEM and then subtracting it from the real interferograms. For this aim an accurate DEM of the area with a 20 m posting has been employed. On the best differential interferograms phase unwrapping has been performed after an adaptive filtering, by applying a region growing algorithm. In order to avoid the introduction of further errors, areas of low phase correlation and consequent difficulty in phase unwrapping have been masked, limiting the analysis to reliable information. Finally, the unwrapped differential phase has been converted into displacement in cm along the satellite line-of-sight and geocoded according to the projections and postings of the employed DEM. The final results of the interferometric processing consist of several multi-temporal displacement maps measured along the line-of-sight of Envisat descending orbit (23° from the vertical circa E-W directed).

4. RESULTS

The long term differential interferograms processed over the city of Morelia, spanning a time interval of 350-450 days, clearly revealed the presence of phase signals related to ground displacements in the urban area, as shown in Fig.2. Two different displacement patterns were detected: small but strict variations of the
phase along preferential directions a few kilometres long, mainly oriented along the NE-SW direction and sub-circular bowls with a diameter of a few hundred meters.

Figure 2: Differential interferogram over the Morelia city spanning the time interval 18/12/2004-03/12/2005.

The best differential interferograms, in terms of coherence and absence of clear atmospheric artefacts, after phase unwrapping and geolocation have been converted into ground displacement map along the satellite l.o.s. (Fig.3 and Fig.4). By importing these maps within a GIS environment and overlaying them with other thematic layers, such as a detailed topographic map, the location of the declared wells and the most evident faultings, as mapped by field surveys carried out in the last years, it has been possible to notice a clear correlation between the registered movements (away from the sensor) and the location of the main tectonic structures.

In particular, movements were registered along the La Paloma fault, the Central Camioniera cracking and the La Colina cracking. Displacement rates measured by the DInSAR analysis between the 2003 and the 2005 range between -1.0 and -3.5 cm/year and they seem to be constant along the monitored period. Apart from the movements along the described faults the sub-circular pattern of deformation was interpreted as a subsidence bowl connected to the presence of an important well for the supply of the municipal aqueduct. Field surveys carried out during July 2006 allowed to check the presence of damage to buildings and man-made structures along the areas detected by the DInSAR analysis, where already in the past the movement evidences were identified (Fig.5).

Currently, the displacement maps provided by the DInSAR processing are analyzed along with ancillary data, such as piezometric maps and stratigraphic data, in order to understand the spatial distribution of the movements and the causes of the differential settlements. On the other hand, the InSAR measurements will be validated through the acquisition of GPS measurements on a benchmark network installed since 2005.

Figure 3: Line-of-sight displacement maps over the Morelia city spanning the time interval 12/07/2003-13/11/2004.

The DInSAR analysis over Querétaro identified a deformation field characterized by two separate domains: a stable area corresponding to the Eastern portion of the city and, separated by a clear discontinuity oriented in the NNW-SSE direction, with a length of more than 3 km, a very active area on the Western side of the city, in the industrial district, with several narrow interferometric fringes (Fig.6 and Fig.8). Mono-dimensional phase unwrapping carried out along a few cross sections revealed that deformation rates...
across the discontinuity reached values of about 7 cm/year and 6.5 cm/year in 2005 (Fig.7 and Fig.9).

The geolocation of the differential interferograms and the comparison with the main discontinuities, as reported by several authors, confirmed that the discontinuities correspond to the main fault of the Queretaro city, namely the 5 de Febrero fault. Field checks identified a clear morphological evidence of the movement along such a tectonic structure, even if due to the industrial nature of that portion of the city damaged buildings were not so numerous.

The last city analyzed in the first part of the research is Celaya. Even in this case ground displacements were detected in the middle of the urban area, along two major discontinuities circa N-S oriented (Fig.10) with rates of 2-3 cm/year. In addition, two clear subsidence bowls were identified in the Northern part of the city, probably connected to the industrial activity and the consequent ground-water exploitation.

Figure 5: Morphological evidence of ground settlements along the “Central Camioniera” cracking in the city of Morelia.

Figure 6: Differential interferogram over the Querétaro city spanning the time interval 12/07/2003-13/11/2004.

Figure 7: Displacement profile related to the 12/07/2003-13/11/2004 couple, obtained through the mono-dimensional phase unwrapping of the phase along the AB section crossing the 5 de Febrero fault. For the section location see Fig.6.

Figure 8: Differential interferogram over the Querétaro city spanning the time interval 18/12/2004-03/12/2005.

Figure 9: Displacement profile related to the 18/12/2004-03/12/2005 couple, obtained through the mono-dimensional phase unwrapping of the phase along the AB section crossing the 5 de Febrero fault. For the section location see Fig.8.
Field surveys carried out over the areas affected by movements, as revealed by the satellite analysis, allowed to identify clear evidences of vertical movements, with scarps 2 m high at some locations along the main faults (Fig.11).

5. CONCLUSIONS

The analysis, carried out in the first part of the study only over the cities of Morelia, Queretaro and Celaya, revealed the presence of ground displacements along the linear structures identified in the field and reported in the literature. The InSAR analysis confirmed how the tectonic structures of the MVB control the ground settlements. Displacement rates up to 5-6 cm/year have been registered in the Queretaro valley, while in Morelia and Celaya the registered velocities reached few centimetres per year. Furthermore, the obtained deformation maps enabled to extend the mapping of the main faultings even over urban areas not yet identified by field surveys, due to the still scarce superficial evidences. To improve the understanding of the ongoing phenomena, the displacement maps provided by the InSAR processing are currently analyzed along with ancillary data, such as piezometric maps, geologic maps and validated with the available in-situ measurements.

5. REFERENCES