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Application of SqueeSAR™ to the characterization of deep seated gravitational slope deformations: the Berceto case study (Parma, Italy).

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Abstract SqueeSAR™ SAR interferometry is today one of the most advanced technologies for surface deformation monitoring capable of overcoming most of the limitations of conventional differential radar interferometry. It exploits long temporal series of satellite radar data, acquired over the same area of interest at different times, to identify "natural radar targets" where very precise displacement information can be retrieved.

Thanks to its capability to detect millimetre level displacements over long periods and large areas, SqueeSAR™ analysis can be considered complementary to conventional geological and geomorphological studies in landslide detection and monitoring, supporting the performance of landslide inventories at regional scale. The availability of surface displacement time series for all the radar benchmarks identified makes it also possible to change the scale of the analysis from regional to local, allowing an in depth study of the evolution of single instability phenomena, supporting the design of traditional monitoring networks, and even verifying the efficiency of remedial works.

The above approach was applied to study the Berceto deep seated gravitational slope deformation (DSGSD) (Parma, Italy) by processing satellite SAR data relevant to the 1992-2000 time span. By combining results obtained in both ascending and descending acquisition geometries, it was possible to retrieve both vertical and E-W components of surface displacements.

A correlation with the results of the geophysical investigations will be proposed, with a preliminary interpretation of the surface displacement trends in the upper part of the slope.

Keywords: InSAR, permanent scatterers, DGSD, Berceto.

Introduction

The Berceto village is located near the top of an unstable slope, characterized by periodical reactivations often following intense meteorological events. These reactivations have been responsible for damages to buildings and infrastructures since a long time. The Berceto unstable slope is reported in the Italian Landslide Inventory (IFFI) Project, partly funded by ISPRA (Italian Institute for Environmental Protection and Research).

Geophysical surveys and borehole investigations have been recently carried out in order to obtain subsurface data enabling a better understanding of the slope behaviour. Eight DC resistivity tomography profiles were recorded in the upper part of the slope and continuous-core boreholes were drilled.

At the end of last year, satellite radar data have been processed with SqueeSAR™ technique, based on an algorithm developed by Politecnico di Milano (POLIMI) and licensed exclusively to TRE, which enables to overcome the errors introduced into signal phase values by atmospheric artefacts, which typically affect the traditional interferometric approach. By exploiting the ESA (European Space Agency) ERS1-2 archives, surface displacement data relevant to 1992-2000 period were obtained.

An integrated approach based on the correlation among the above data, aimed at assessing the risk related to the landslide evolution, is still in progress; some preliminary results will be presented in this paper.

Geological setting

The Berceto area is located along a regional SW-NE tectonic discontinuity, separating two different sectors of the Apennine chain: the Ligurian-Emilian to the NW and the Tuscan-Emilian to the SE. In the NW Apennine segment thick External Ligurian Units are preserved; in the SE segment, more exhumated by tectonic uplift, the underlying foredeep units are exposed (Bernini et al, 1997). This tectonic uplift took place during Pleistocene (Argnani et al, 2003), accompanied by extensional NW-SE faults on the Tyrrhenian side of the Apennines (Bernini and Papani, 2002).

In the Berceto area, close to the divide between the Manubiola and Baganza rivers (fig. 1), the transversal deformation band produced SW-NE sinistral strike-slip faults, NNE-SSW extensional faults, and superimposed NW-SE normal faults (Bertoldi et al, 2004). The stack of Ligurian Units largely outcrops (Vescovi, 2002). The overturned M.Caio Flysch, affected by SW-NE high-angle transpressive faults is tectonically overlain by Shaly Chaotic Complex, consisting of black and grey shale, with pervasive development of scaly fabric (Pini, 1999), often associated with ophiolitic bodies. The Shaly Chaotic Complex is overthrust by the Scabiazza Sandstone, about 100 m thick, stratigraphically overlying the Mt. Rizzone Shale and Limestone, outcropping in excavations located near the village (Bertoldi et al, 2004). The Scabiazza Sandstone consists of a turbidite sequence showing thin-bedded shaly and marly lithofacies, alternated by medium-bedded sandstone lithofacies. This unit was affected by S-verging recumbent folds and gently-dipping detachment faults, crossed by high-angle fault systems: the NE-trending sinistral transpressive faults, the NNE-SSW normal faults and the NW-SE late normal faults.

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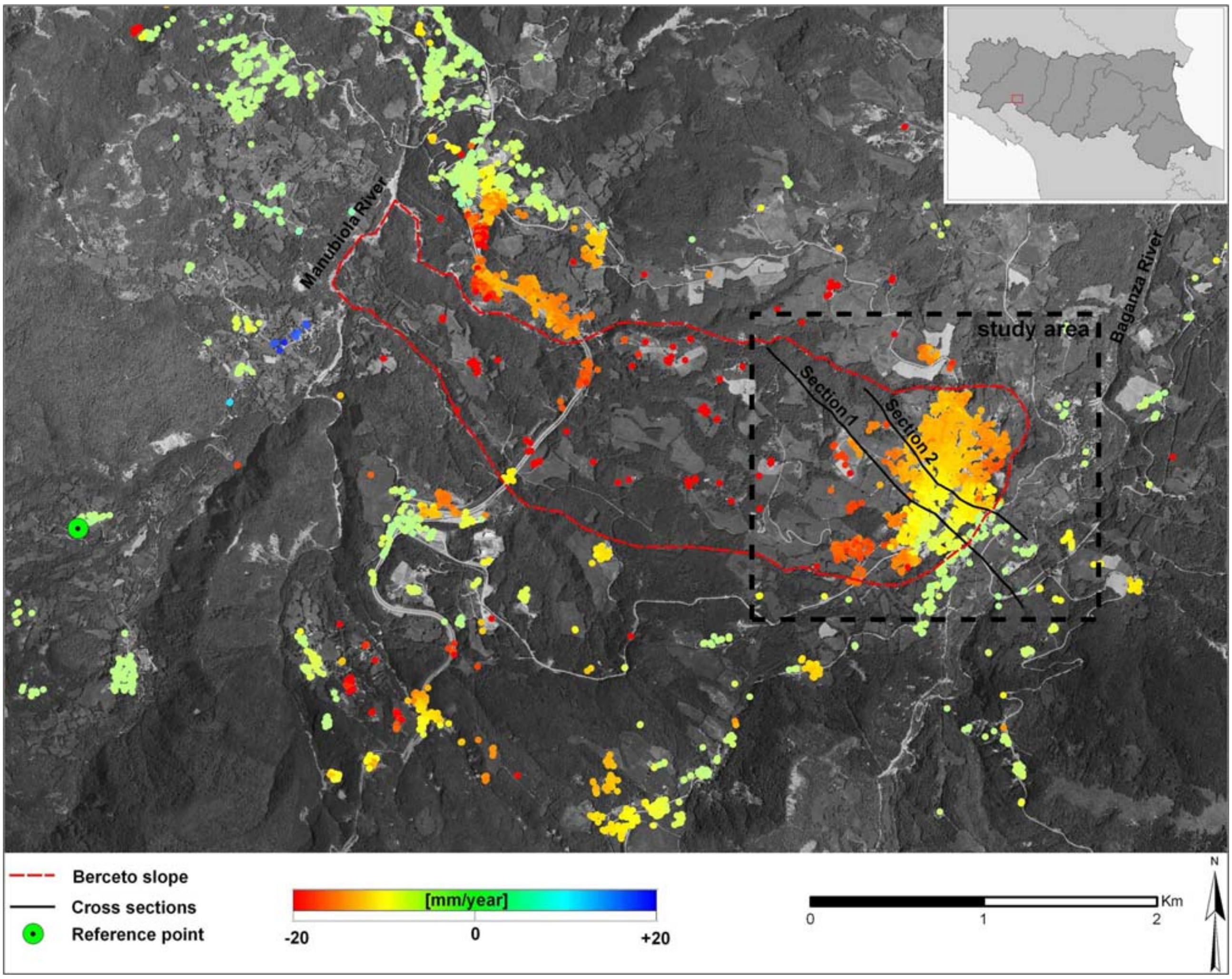

Figure 1 Location map of the study area, with the average yearly surface displacement velocity measured along the satellite LOS.

This structural framework and the lithological characteristics of the Scabiazza Sandstone are considered responsible for the development of a trench at the top of the Berceto slope.

A 50 m borehole drilled in the village in 2001 found Upper Pleistocene laminated lacustrine sediments about 25 m thick (radiocarbon dating 29,620±290 14C yr B.P.) deposited in the trench (Unit 5 in Bertoldi et al., 2004). The lacustrine sediments overlay a sedimentary breccia containing very weathered clasts of sandstone in silty matrix (Unit 6 in Bertoldi et, al., 2004) and passing up into peat (radiocarbon dating 11,150±70 14C yr B.P.). The lacustrine sequence was affected by folding and exhibits shear surfaces, testifying both compressive and, likely, extensive deformation occurred during the Late Pleistocene gravity-induced deformation of the Berceto slope; these deformative phases may have produced either a rotational rockslide (Bertoldi et al, 2004) or sliding over a shear surface gently dipping towards NW (Corsini et al., 2006).

Surface displacements

In the early 90's the first data on Earth's surface provided by Synthetic Aperture Radar (SAR) mounted on satellites, have imparted a significant breakthrough in the field of Earth Observation. Since then new unthinkable perspectives have been gained on surface deformation phenomena analysis and monitoring. The advanced survey techniques of Earth's superficial displacements from satellite are known as SAR Interferometry (InSAR).

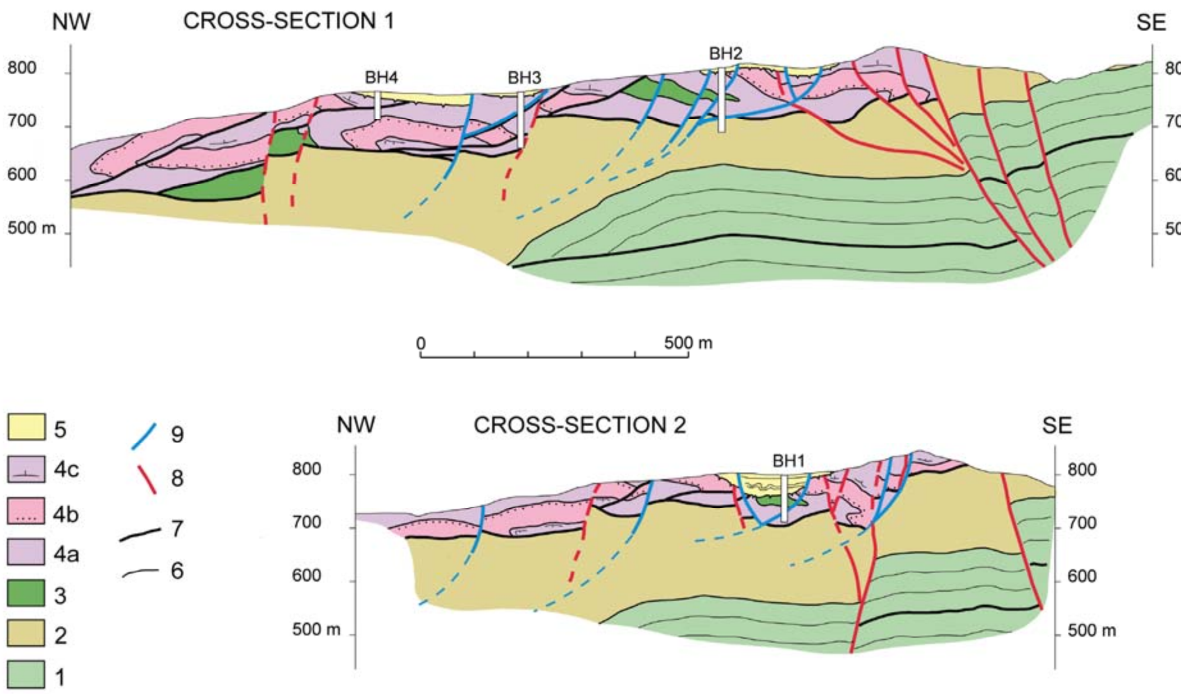

Figure 2 Geological cross sections 1 and 2. Key to symbols: 1, Mt. Caio Flysch (thick-bedded marlstones); 2, Shaly Chaotic Complex (with ophiolite breccias); 3, Mt. Rizzone Shale and Limestone; 4, Scabiazza Sandstone (4a, Thin-bedded shale and sandstone lithofacies; 4b, Medium-bedded sandstone lithofacies; 4c, Thin-bedded marls and sandstone lithofacies); 5, Late Pleistocene Lacustrine deposits; 6, stratigraphic boundary; 7, overthrust and low-angle detachment faults; 8, high-angle faults (shifted by gravity where hatched); 9, gravitational faults (inferred where hatched).

SAR data processing techniques have been developed and improved by Radar Group of Electronics Department of the Politecnico of Milano (POLIMI) and after by Tele-Rilevamento Europa (TRE), first spin-off of POLIMI. TRE was granted exclusive license called Permanent Scatterers (PS) technique, or PSInSAR™ (Ferretti et al., 2001). The SqueeSAR™ technique (Ferretti et al., 2011) is a second generation algorithm, an evolution of PSInSAR™ technology, that searches for 'targets' on the ground that return stable radar reflections over time back to the satellite.

As well known, a SAR image is a collection of signals coming from different types of radar targets, either natural (forests, rocks, etc) or man-made (buildings, bridges, poles, etc). The signal recorded by the sensor can vary abruptly even in neighbor pixels, depending on the different radar signatures of the illuminated objects and the acquisition geometry. In general, image pixels where InSAR data can be extracted belong to two families of targets: point-wise targets (Permanent Scatterers, PS), where the reflected energy comes from a single or a few connected pixels, and Distributed Targets (DS). A Distributed Scatterer (DS) corresponds to a homogeneous area spread over a group of pixels in a radar image, like for example an agricultural field, a forest, a debris covered area. The characteristics of the radar returns coming from all pixels corresponding to the same DS, are "statistically homogeneous", i.e. the interaction between the radar target on ground and the electromagnetic wave is almost identical and can be modeled by the same probability density function.

While PS typically correspond to point-wise scatterers exhibiting a very high Radar Cross Section (RCS), the amplitude of the radar return of a pixel belonging to a DS is usually much weaker, due to the lack of a dominant scatterer in the resolution cell, and is characterized by lower SNR. Indeed, if the estimation of displacement rate and elevation values is performed on a pixel-by-pixel basis across a DS, results are very noisy. However, by averaging the signal of all the pixels belonging to the same DS, it is possible to significantly improve the estimation quality, obtaining SNR values similar to the PS, at the cost of a loss of spatial resolution due to the averaging process. Thanks to typical remote sensing characteristic and in particular, the ability of covering vast remote areas of Earth's surface (from a few to thousands of square kilometres) and to the ability of estimating displacement with millimetre accuracy, SqueesAR™ is a very effective tool for high-precision monitoring of surface displacements, and can be applied at different scales, from regional to single building.

The SqueeSARTM analysis provides for each measurement point the average yearly displacement velocity value and a displacement time history.

Displacements are measured along the "line of sight" (LOS) of the radar beam. The satellites fly over the Earth along polar orbits, and therefore pass over the area of interest in two possible geometries: ascending, flying from south to north, and descending, from north to south. The availability of displacement data in both ascending and descending geometries over the same area enhances the coverage of the study area and enables the estimation of vertical and E-W horizontal displacement fields.

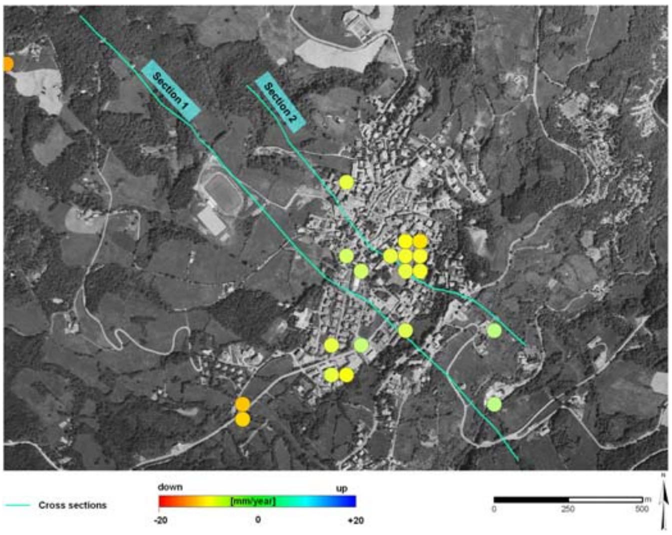

Figure 3 vertical average yearly displacement rate provided by SqueeSAR™ analysis

Two data sets of 77 descending and 27 ascending SAR scenes acquired by ERS-1 and ERS-2 satellites were processed, covering the period July 1992 - January 2001. More than 6000 measurement points in both acquisition geometries were identified within the study area.

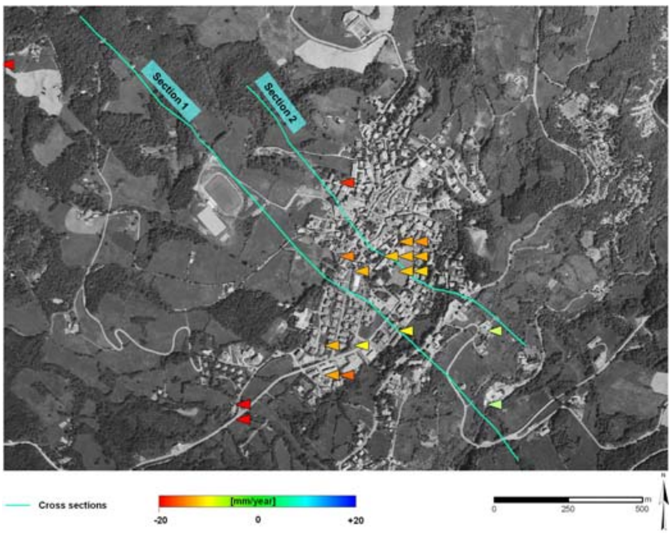

Figure 4 E-W horizontal average yearly displacement rate provided by SqueeSAR™ analysis

The main results of the analysis are summarized in the following points:

- the average yearly displacement rate (LOS displacements, descending geometry) is 10-15 mm/yr in the urbanized area, 20-30 mm/yr near the foot of the slope, with maximum values up to 50 mm/yr measured in the mid part of the slope
- the yearly displacement rate distribution evidences the upper limit of the sliding area, corresponding to the eastern limit of the urbanized area
- within the urbanized area and the upper right part of the Berceto slope, seasonal displacement cycles, sometimes superimposed on the average displacement trend, seem to be present; the amplitude of the seasonal cycles reaches maximum values of about 10 mm;
- in the lower left part of the Berceto slope, the displacement time history seems to show an increase of displacement rate during spring;
- the estimation of vertical from E-W horizontal components obtained by geometrically combining data acquired in ascending and descending geometries indicates that the vertical component prevails in the upper part of the slope, while the E-W horizontal component in higher than the vertical one in the lower part of the slope.

Subsurface structure of the upper Berceto slope

Eight DC resistivity tomography profiles, with 126 smart electrodes spaced 11.5 m for a total length of 1437.5 m each, crossing the upper part of the Berceto slope including the village were recorded. The investigation depth was about 250 m. According to the lithology of the geological units recognized in the study area, three geoelectric units were recognized: resistive (coherent lithologies), conductive (shaly lithologies) and intermediate (heterogeneous lithologies and/or high water content).

Two resistivity profiles, together with their geological interpretation (Figure 5 and 2 respectively), have been selected as representative of the geological and structural framework of the Berceto slope. From a general point of view, the following sequence was recognized, from top to bottom: an upper intermediate resistivity unit (IRU), a central conductive unit (CU) and a lower resistive unit (RU). A more detailed description of the selected cross section follows.

The resistivity profile 1 exhibits the IRU (Scabiazza Sandstone) characterized by thin-bedded shales and sandstones, including more resistive medium-bedded sandstones up to 100 m thick in the NW part. The upper IRU is dislocated by discontinuities interpreted both as tectonic faults and/or gravitational sliding surfaces. Such discontinuities are SE-dipping near the Baganza valley, NW dipping on the Berceto slope. The central CU (Shaly Chaotic Complex) even if more continuous than the upper one, with an average thickness of about 100 m, appears stretched in at least three points, one of which corresponding to the deepening of the lower RU in the NW part of the cross section. This lower RU was interpreted as the Mt. Caio Flysch, which exhibits an antiformal geometry faulted in the NW part, where the unit is about 150 m deeper.

The resistivity profile 2 crosses the Berceto village and the trench with the lacustrine sediments previously described, evidenced by high conductivity values. The upper IRU shows higher conductivity values compared to cross section 1, probably related to a higher water content in more fractured and permeable levels. The central CU (Shaly Chaotic Complex) has an average thickness of about 100 m, and is clearly stretched in the NW part of the section. Compared to cross section 1, the lower RU (Mt. Caio Flysch) is less evident but visible at the same depth.

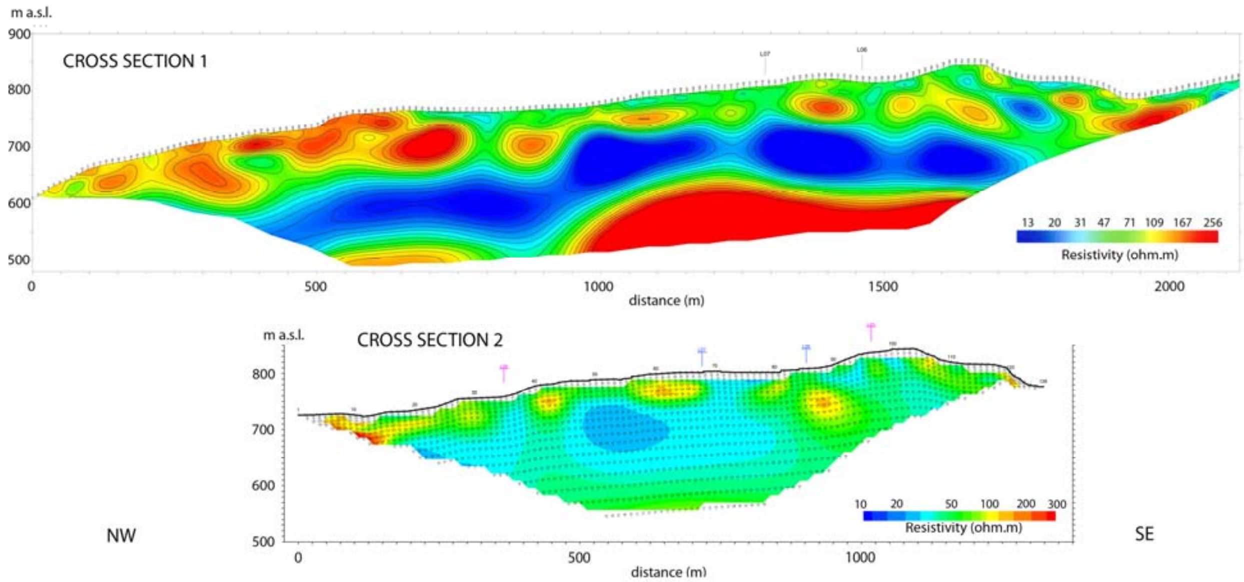

Figure 5 DC resistivity tomography profiles 1 (by GEOINVEST s.r.l. Piacenza, up) and 2 (by SGG s.r.l. Siena, down).

Geoelectrical data were integrated with borehole data and structural data collected on the outcrops close to the village and along Baganza valley, in order to provide a geological interpretation of the subsurface structure of the Berceto slope.

The geological cross section 1 (corresponding to resistivity profile 1) shows in the right part SW-NE high-angle faults affecting the Mt. Caio Flysch; under the Berceto village this unit exhibits an antiformal structure, visible in outcrop along the Baganza river. The Mt. Caio Flysch is overthrusted by the Shaly Chaotic Complex, which is overthrusted by the Scabiazza Sandstone. This last was deformed by a pre-Apennine S-verging folding, detached by N-dipping low angle surfaces and by high angle faults related to Apennine tectonics. The high-angle faults appear shifted by NW-dipping gravitational faults, that could explain the presence of plastic clay-rich breccia with arenaceous blocks levels identified in boreholes BH2 at a depth of 40 and 90 m respectively (fig. 2). The presence of gravitational faults could explain the stretching observed within the Shaly Chaotic Complex and the higher surface displacement rate pointed out by satellite interferometry. The Berceto lacustrine sequence, recognized in both boreholes BH3 and BH4 could have probably been dislocated by gravitational faults. About 10 m of lacustrine deposits, corresponding to the Unit 6 (Bertoldi et al., 2004), were encountered in Borehole BH3; the same unit, overlain by 4 m thick laminated lacustrine sediments (Unit 5, Bertoldi et al., 2004), deformed by extensional shearing, were found in borehole BH4. Such laminated deposits appear 13° dipping, meaning the occurence of rotational movements.

From a general point of view the geological cross section 2 (corresponding to resistivity profile 2) shows the same geological and structural framework of section 1. About 25 m of laminated lacustrine deposits were encountered in borehole BH1, within the trench delimited by gravitational faults corresponding to the Berceto hollow. A 2 m thick plastic interval was found at a depth of 58 m, and interpreted as the evidence of a gravitational fault.

Discussion and conclusions

Hypotheses about the evolution of the Berceto slope were advanced after integrating surface and subsurface data and observations with literature data.

The structural framework of the Berceto area indicates that the upper Berceto slope was affected by gravitational faults (Persaud and Pfiffner, 2004; Ustaszewski and Pfiffner, 2008). One possible mechanism for these gravitational slope processes are the “deep-seated gravitational slope deformations” (DGSD) by Dramis and Sorriso-Valvo (1994), recognised in several parts of the Northern Apennines (D’Amato Avanzi and Puccinelli, 1996; Coltorti et al, 2009).

The uppermost portion of the Berceto slope is characterized by the tectonic uplift related to transpressive tectonics; this structure may be a relevant factor for the development of the DGSD (Dramis and Sorriso-Valvo (1994).

Several gravitational faults developed close to the north-western side of the antiformal stacking of the buried Mt. Caio Flysch. Within the Scabiazza Sandstone gravitational faults using pre-existing discontinuities such as tectonic faults and foliation planes and the kinematics seems a rotational sliding (Cruden and Varnes, 1996). Through the Shaly Chaotic Complex, characterized by lithologies affected by pronounced foliation, the gravitational deformations may develop with more ductile mechanical behaviour, resulting in failure surfaces flattening towards the valley floor or a deep-seated creep with very slow movement rates (Hutchinson, 1988).

The evolution of the DGSD was probaly responsible for the formation of a depression larger than the present Berceto hollow, in the upper part of the slope, where the lacustrine sequence was deposited. According to radiocarbon data, this lacustrine sequence was dislocated during the Holocene. The difference in elevation between the bottom of the lacustrine basin encountered in boreholes BH1 and BH4 is about 50 m, which could correspond to an horizontal displacement of more than 100 m, according to the present-day morphology of the slope. Under this hypothesis the average yearly displacement rate is consistent with the present-day surface displacement rate measured from 1992 to 2000 with satellite interferometry.

Surface displacement data are also consistent with the hypothesis of gravitational faults reaching the Shaly Chaotic Complex. The distribution of vertical vs horizontal component ratio indicates the presence of rotational sliding surfaces; moreover the highest displacement rates occurr in the central part of the slope, corresponding to the top of the deep antiformal structure, where the deformation of the slope seems to affect a thicker sequence.

Finally, the interferometric data analysis provided some evidences of correlation between landslide activity and precipitation. Seasonal displacement cycles observed in the the urbanized area and the upper right part of the Berceto slope can be explained as the result of swelling-shrinkage deformation cycles, typical of the clayey deposits, i.e. the lacustrine sequence. Moreover displacement rate increase during spring in the lower left part of the Berceto slope could be an evidence of creep phenomena superimposed on the deep deformation trend, related to water circulation.

This first attempt of integration between surface displacements provided by SqueeSARTM analysis and subsurface data provided by geophysical and borehole investigations suggested that the evolutional model proposed for the Berceto DGSD is nevertheless more complex than expected. Further investigations are needed in order to gather more surface and subsurface data. Moreover a new ground based monitoring system is being installed, in order to integrate the results obtained by satellite radar interferometry and improve the knowledge of the slope dynamics.

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