5th Joint International Symposium on Deformation Monitoring (JISDM), 20-22 June 2022, Valencia, Spain
DOI: http://doi.org/10.4995/JISDM2022.2022.13818

Landslide monitoring using geotechnical, UAV, GNSS and MTInSAR instrumentation

Nikolaos Depountis[1], Katerina Kavoura[1], Konstantinos Nikolakopoulos[1], George Drakatos[2], Panagiotis Argyrakis[3], Panagiotis Elias[4], Nikolaos Sabatakakis[1]

[1] University of Patras, Department of Geology, Greece, (ndepountis@upatras.gr; kavoura@upatras.gr; knikolakop@upatras.gr; sabatak@upatras.gr)
[2] National Observatory of Athens, Institute of Geodynamics, Greece, (g.drakat@noa.gr)
[3] University of West Attica, School of Engineering, Department of Surveying and Geoinformatics Engineering, Greece, (pargyrak@uniwa.gr)
[4] National Observatory of Athens, Institute for Astronomy, Astrophysics, Space Applications and Remote Sensing, Greece, (pelias@noa.gr)

Key words: *landslides; real-time monitoring; kinematics; inclinometers; interferometry; GNSS; UAV*

ABSTRACT

Many mountainous villages have been struck by landslides in Western Greece due to growing urbanization and uncontrolled land use in landslide prone areas, without considering the engineering geological environment. The presence of the tectonically highly sheared and weathered geological formations of the alpine basement (such as flysch) and the intense geomorphological relief, strongly contribute to the periodically induced instability phenomena mainly triggered by heavy rainfalls and extreme meteorological events. The current research combines long-term monitoring of the parameters connected to the landslide activity with the real-time kinematics observation in a dense-populated mountainous village located in the Region of Epirus in Greece. The landslide movements evolve very low velocity values at different depths; thus, the landslide cases can be characterized as complex and "extremely slow". The long-term monitoring is carried out by several in-place and portable inclinometer probes that permit the detailed observation of subsurface displacements for an extended period. In addition, GNSS measurements, very high-resolution multitemporal interferometry (accompanied with the installation of corner reflectors) and Unmanned Aerial Vehicle (UAV) photogrammetric surveys are used for the monitoring of surface deformation. All instrumentation is installed in the wider area of the landslide zone and one of the main goals of this approach is to combine long-term monitoring of the parameters connected to the landslide activity with the observation of the landslide kinematics in real-time.

I. INTRODUCTION

Nowadays, an active landslide can be monitored using different methods and approaches. These include geotechnical instrumentation like slope inclinometers, high resolution images acquired by Unmanned Aerial Vehilcles (UAVs), Geodetic Global Navigation Satellite Systems (GNSS) receivers and multitemporal interferometry (MTInSAR).

Vertical inclinometers (in-place and portable) are widely used to determine the magnitude, rate, direction, and type of landslide movement in several depths. Along with the appropriate kinematic analysis and movement evolution modeling (Kavoura *et al.,* 2020), this information is important for understanding a landslide's cause, behavior, and remediation.

In addition, when extreme meteorological events trigger landslides, the data obtained from meteorological stations are also important. The quantification of the rainfall patterns that act as trigger mechanisms on landslides in a specific area is of great importance when analysis of selected landslide cases is required and this may be used as a landslide forecasting tool in an applied form (Lainas *et al.,* 2021).

Following the above, the rapid development of the Geodetic global navigation satellite system (GNSS) receivers allows landslide monitoring, especially on the landslide's surface with increasing accuracy. The deformation monitoring with global navigation satellite system (GNSS) measurements is a well-known method which can be employed both for continental scale and local phenomena such as landslides. A geodetic GNSS receiver is used when a high level of accuracy (greater than centimeter) is needed (Leick, 2004).

Lately, UAVs are widely used on landslide precision mapping as it seems to be more efficient than the classical topographic survey, resulting in the creation of orthophotos and Digital Surface Models (DSMs) with extremely fine resolution (Nikolakopoulos *et al.*, 2017a). In this context, high-resolution and low-cost images acquired by UAVs are used to create and update maps by providing orthophotos with sub-decimeter accuracy (Koeva *et al.*, 2018). In addition, UAV-based point clouds and DSMs prove comparable to corresponding products derived from terrestrial laser scanning (TLS) survey (Mancini *et al*., 2013). As a result, repeated UAVs photogrammetric campaigns are proved to be an excellent tool for precise landslide mapping and monitoring aiming at the evaluation of the landslide activity (Nikolakopoulos *et al*., 2017b; Kyriou *et al.,* 2021a; 2021b).

Finally, the exploitation of Persistent Scatterers interferometry (PSI) and Small BAselines Subset (SBAS) as well as the corner reflector (CR) methodologies allows an increased signal-to-noise ratio for monitoring crustal deformation and surface landslide movements.

In this work, results of the combined use of slope inclinometers, along with high-resolution images acquired by UAVs, GNSS measurements and multitemporal interferometry for a detailed landslide monitoring are presented. For this purpose, all the relevant instrumentation has been installed inside the landslide zones of two residential areas, in Metsovo and Zotiko, which are two well-known villages located in the Region of Epirus in Western Greece. The main goal of this approach is to combine short and long-term monitoring of the landslide's activity and kinematics, which with some minor modifications can be operated as a Landslide Early Warning System (LEWS).

II. SITE DESCRIPTION AND INSTRUMENTATION

Landslide monitoring in the residential area of Metsovo is performed by installing inclinometer casing in several boreholes to permit the detailed observation of subsurface displacements, with the use of two in-place inclinometers (otherwise BH profile digital gauges) and a digital vertical inclinometer probe.

BH profile digital gauges are designed for automatic monitoring of critical depth locations where displacement monitoring request a continuous borehole profiling. The BH profile gauges used in the current research consist of a stainless steel and thermoplastic resin assembly with one fixed wheel (close to the joint) and one spring loaded wheel. Each BH profile has been installed into an inclinometer casing at least 20 m long and is composed by a string of 4 gauges 1 or 2 m long with carbon fiber extension rods and an upper terminal wheel's assembly to close the chain and. Each string is connected to its own datalogger with a single digital bus cable (S430HD digital model) for collecting and transmitting the relevant displacement data.

The digital vertical inclinometer probe used in the current research consists of a) a stainless-steel body with digitalized inclinometer MEMS to measure inclinations in two orthogonal directions, b) two-wheel assembly at a distance of 50 cm to slide along the grooves of the inclinometer casing, c) an inclinometer cable 50 m long connected to the probe and d) an android mobile readout unit for collecting the data.

Additionally, to the above, GNSS receivers, scatterers, and a meteorological station have been installed for the landslide's surface displacement observation and the collection of hydrometeorological data (Figure 1). The GNSS receivers and the meteorological station have been adjusted to continuously collect real-time data, whereas the scatterers are used for periodically scheduled SAR acquisitions.

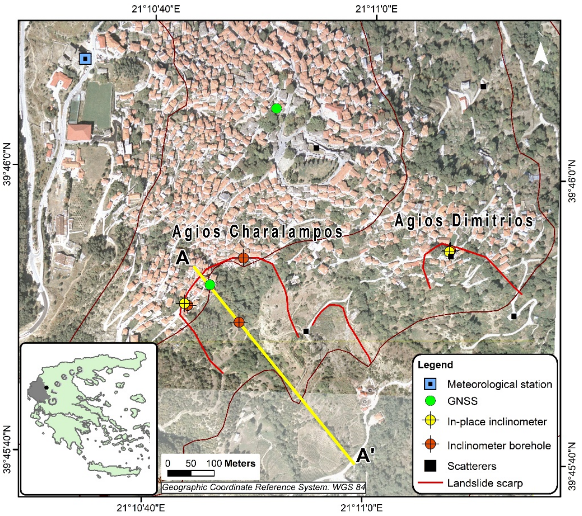


Figure 1. The study area of Metsovo in Greece and the installed instrumentation (cross-section AA' presented in Figure 3 is depicted with a yellow line).

On the other hand, landslide monitoring in the residential area of Zotiko is performed by installing inclinometer casing of 25 m in each of the two boreholes drilled for this purpose and by using a digital vertical inclinometer probe for the relevant subsurface displacement. A GNSS receiver and a meteorological station have also been installed in the surrounding area (Figure 2).

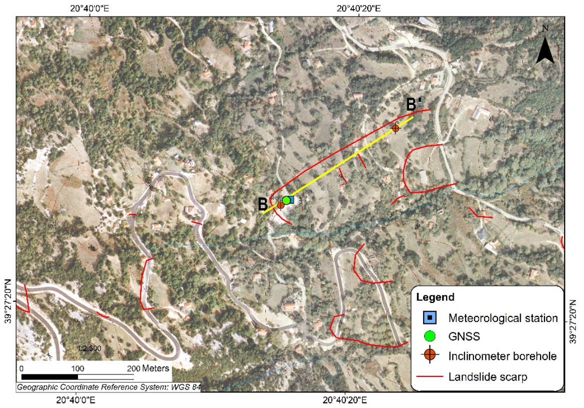


Figure 2. The study area of Zotiko in Greece and the installed instrumentation (cross-section BB' presented in Figure 5 is depicted with a yellow line).

III. GEOTECHNICAL INSTRUMENTATION FOR LANDSLIDE MONITORING

In both areas, Metsovo and Zotiko, the tectonically highly sheared and weathered geological formation of flysch and the intense geomorphological relief, strongly contribute to periodically induced landslide phenomena, mainly triggered by heavy rainfalls and extreme meteorological events. The landslides in both areas are still active and evolve extremely low-velocity values at different depths (2-16 mm/year); thus, the studied landslide cases can be characterized as complex and according to the WP/WLI (1995) guidelines as "extremely slow".

In the area of Metsovo three different areas of landslide events have been identified since 2010 with the largest one in the south-western part of the village. The landslide has a crown length of approximately 90 m and extends downwards with a length of approximately 200 m (Figure 1). From the geological and geotechnical investigation performed in the surrounding area, it seems that a main translational displacement slide has been occurred in the weathered flysch, which can be divided into two overlapping (successive) and a rotational slide with the maximum depth of the sliding surface approaching and may be exceeding the 30 m (Figure 3).

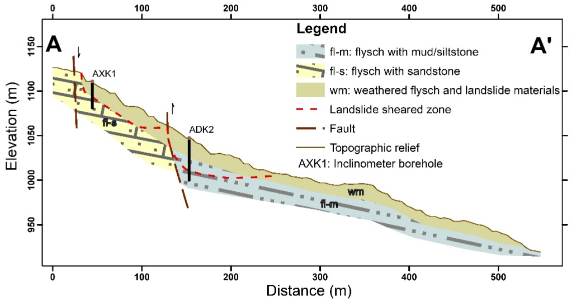


Figure 3. Geological cross-section AA' in Metsovo.

The general kinematics of the sliding zone suggests that this is a complex landslide where different types of movements take place in different areas of the sliding mass, usually simultaneously. According to the inclinometer observations the depth of the landslide sheared zone varies from 5-10 m near the residential area up to 25-30 m to south-east (Figure 4).

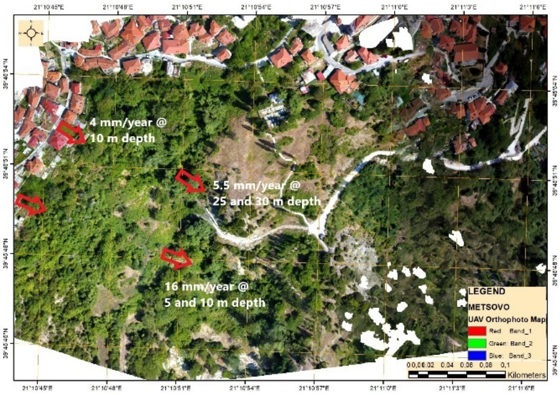


Figure 4. Orthophoto map of Metsovo (the red arrows represent the direction and rate of subsurface movement in mm/year at several depths below the ground surface).

The almost constant speeds 4 to 16 mm/year of the subsurface ground movement recorded with the use of portable inclinometer porbes during the last 10 years in the whole landslide area, identifies this landslide as "extremely slow", very close to the "slow" limit. Regarding the measurements derived by the in-place inclinometers, from October 2020 until October 2021, a small movement of 0.25 mm/year has been recorded in the landslide's western part at a depth of 5 to 10 m.

In the village of Zotiko several areas of landslide events have been identified since 1979 with the largest one located in the north-eastern part of the village. The total length of the sliding mass is approximately 300 m and its width 130 m. (Figure 2). From the geological and geotechnical investigation performed, it seems that a slow translational displacement slide has been occurred inside the scree material and the weathered flysch, at depths varying from 10 to 15 m (Figure 5).

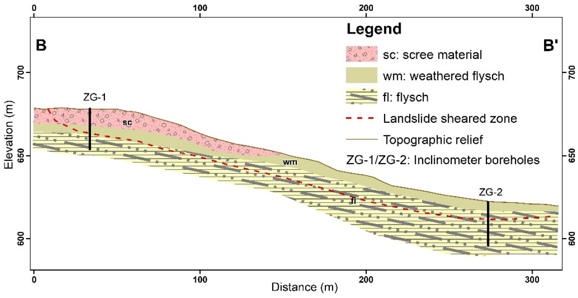


Figure 5. Geological cross-section BB' in Zotiko.

The general kinematics of the sliding zone certifies that this is a complex landslide with translational geometry. According to the inclinometer readings the depth of the landslide sheared zone varies from 14 m next to the landslide scarp up to 11 m further to north-east. The speeds of 2 to 10 mm/year of the subsurface ground movement recorded with the use of portable inclinometer probes within the period 2018-2020 in the whole landslide area, identifies this landslide as "extremely slow" (Figure 6).

Figure 6. Orthophoto map of Zotiko (the red arrows represent the direction and rate of subsurface ground movement in mm/year at several depths below the ground surface).

IV. UNMANNED AERIAL VEHICLE SURVEY

In both areas of Metsovo and Zotiko photogrammetric annual UAVs campaigns were planned and performed at 100 m above the ground level. UAV imagery was obtained using a DJI Phantom 4, which is equipped with a built-in GNSS system and a CMOS camera (12.4 MP) with 4000 × 3000 resolution. The same grid with 80% overlap along and across the track was used every year resulting at 3 cm pixel size of the orthophotos and the DSMs. Furthermore, the same ground control points were used in every campaign. The ground control points were measured with a Leica GS08 RTK GNSS receiver. The UAV data processing was performed in Agisoft Photoscan Professional software. In more details, UAV data were processed according to the Structure from Motion (SfM) photogrammetric technique. SfM constitutes a low-cost and user-friendly technique which combines photogrammetry and computer vision for 3D reconstruction of an object or a surface model (Westoby *et al.*, 2021; Micheletti *et al.*, 2015; Eltner and Sofia*,* 2020).

Three annual sets (2018, 2019, 2020) of high resolution orthophotos and DSMs covering the study areas were finally generated and used for exploring the landslide surface deformation and as base maps for the design of landslide. The generated orthophoto maps of Metsovo and Zotiko, from the 2019 campaign, along with the direction and rate of the landslides movements are respectively presented in Figures 4 and 6.

V. GNSS INSTRUMENTATION AND MONITORING

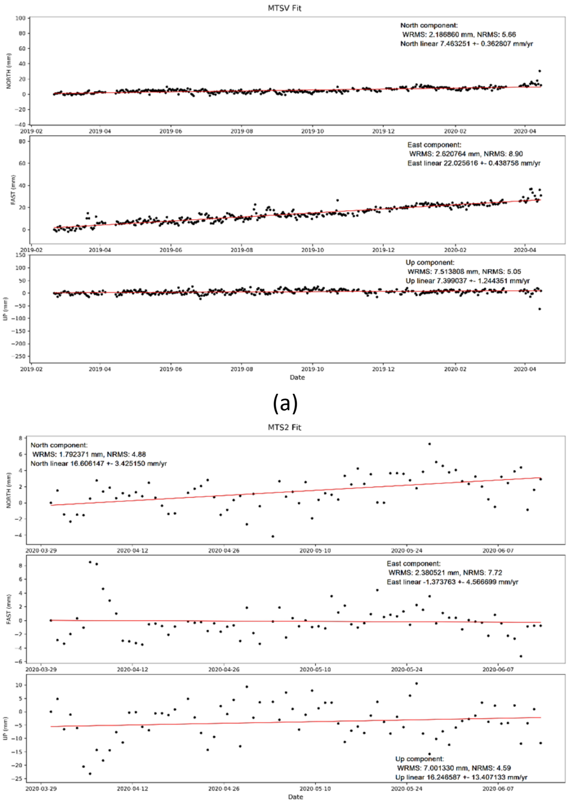
Two GNSS stations were installed in Metsovo (Figure 1) and one station in Zotiko (Figure 2), with code names MTSV, MTS2, and ZOTI, respectively. The stations are equipped with dual-frequency GNSS receivers and continued network connections. The receivers are set to 30-second acquisition and 0 degrees elevation mask. The rinex files are transmitted via wired (MTSV) and wireless/3G (MTS2, ZOTI) internet connection to the central NAS at the University of Patras and checked every day for integrity.

After the integrity checks, the rinex files are processed for quality control with TEQC software to identify excess multipath or signal to noise errors and the data are processed with GIPSY-OASIS, which uses a Precise Point Positioning algorithm to solve the daily position. The tropospheric delays were eliminated in Precise Point Positioning by using appropriate modeling like GPT2 or VMF1 in the processing phase. The elevation mask was used only to remove bad satellite reception especially below 5°.

The solution is saved into a database, and the time series is extracted after the user query. The deformation time series as resolved for the areas of Metsovo and Zotiko are presented in Figures 7a, 7b and Figure 8, respectively.

VI. MULTITEMPORAL INTERFEROMETRY

The exploitation of a large volume of SAR acquisitions of the same ground track, forming a set of differential interferograms, between a single image and all the others, along with the proper application of the so-called method PSI (Ferretti *et al.,* 2011), allows an increased signal-to-noise ratio for monitoring crustal deformation as well as landslide movements.



(a)

(b)

Figure 7. Time series and rate of the surface movement in Metsovo: (a) GNSS station MTSV; (b) GNSS station MTS2.

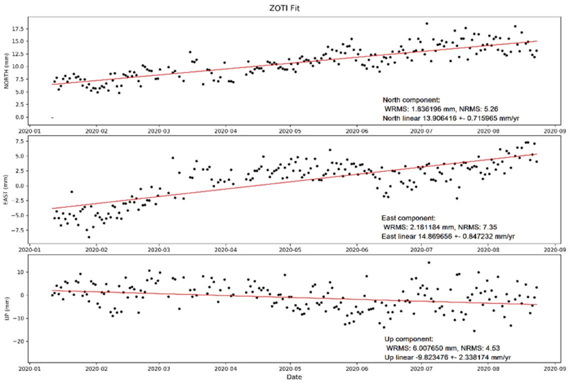


Figure 8. Time series and rate of the surface movement in Zotiko (GNSS station ZOTI).

It is based on the identification of target-scatterers with a stable radiometric behavior in time. This technique ensures the minimization of noise and the measurement of linear or nonlinear deformation phenomena along the Line Of Sight (los). PS (Persistent Scatterers) pixels (scatterers) are identified as those pixels whose phase histories match an assumed model of how displacement varies with time. This functional model of temporal displacement (*e.g.*, linear model) to identify PS, approximate knowledge of how the deformation varies with time is required a priori.

Commonly, deformation is assumed to be steady-state or periodic in nature.

In addition to the PSI approach, the SBAS method (Bernardino *et al.*, 2002), based on different combinations of the available SAR interferograms relative to a study area, is used. SBAS is an extension of the conventional SAR Interferometry (InSAR) techniques and addresses decorrelation and atmospheric delay problems. The SBAS technique relies on an appropriate combination of differential interferograms characterized by a small orbital separation and increases the sampling rate by using all the acquisitions included in the small baseline subsets and preserves the system's capabilities to provide spatially dense deformation maps (Casu *et al.,* 2006). As each of these two techniques is optimized for different models of ground scattering, they are complementary.

The passive CR, which has been implemented in this study, is a metal construction that backscatters the received microwave radiation back to its source. Its shape is triangular trihedral, consisting of three orthogonal and isosceles triangles, with orthogonal sides of 0.4 m. This design is not the one with the maximum backscatter peak gain, but its radiation pattern is wide, having a half-power response width of 40° (Rahmat-Samii, 2007).

In the area of Metsovo ten CRs were installed in five positions prior to the scheduled acquisitions. A pair of them placed back-to-back in each location, each one oriented for the ascending and descending track. The elevation and the azimuth of the focal point of the CRs was set to have maximum backscatter for the incidence angles of 44° for the ascending and 47° for the descending track.

A total number of forty acquisitions of the TERRASAR-X satellite in High-Resolution Spotlight mode were used. Twenty of them were acquired from the ascending track 70 during the period from 7/12/2019 to 5/8/2020 and another twenty from the descending track 47 during the period from 6/12/2019 to 15/8/2020.

To produce the original products of MTInSAR (MultiTemporal InSAR), the ENVI SARscape® software (L3Harris Geospatial, Boulder, CO, USA) software was used. Using both differential interferometry techniques over time, *i.e.*, PSI and SBAS for the ascending and descending orbits, we ended up with four sets of deformation rates for the ground and the overlying structures with different measuring properties. Herein only the SBAS products are presented. These were processed further to (1) remove remaining linear gradients in directions N-S and E-W, (2) calibrate them so that they have a reference (zero) to the GNSS Location and (3) remove unreliable measurements.

In the whole area of Metsovo for the ascending track no extensive deformation is observed apart from certain areas of limited extension within the residential fabric. In the deformation maps of the Distributed Scatterers (DS) for the descending track certain areas with deformations within the residential fabric are observed, which are marked 'a' to 'h' (Figure 9). For example, in the ('h') area no deformation is observed, except at the east.

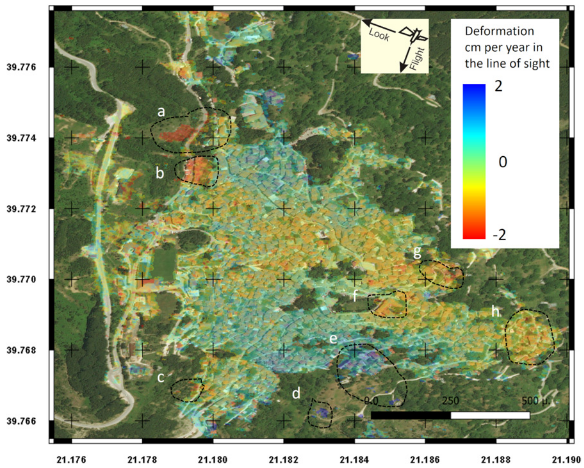


Figure 9. Deformation map of the DS descending track of the Metsovo area.

Concerning the ('d' and 'e') areas extensive failures occur in the residential fabric and the area around the corner reflector is deformed with a value of more than 2 cm/year (Figure 10).

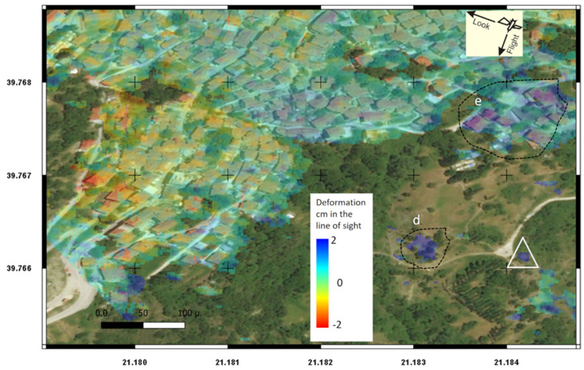


Figure 10. Deformation map of DS of the descending track focused in areas ('d' and 'e'). The white triangle shows the location of the corner reflector.

For the more complete mapping and utilization of satellite data, based on the products of DS for both tracks, vector records (polygons) were created, categorizing the deformation rates in four ranges as can be seen in Figure 11.

Moreover, for each of the polygons, the scatterers' multi-temporal ground deformation rate was created, as shown in a characteristic case in Figure 12.

VII. DISCUSSION

The surface ground movements in Metsovo were recorded with a contribution of very high-resolution data TERRASAR-X acquired for the German Space Agency (DLR) science project. Practical issues and other factors as the low priority of the commercial schedules over those within the DLR science project limited the study period to nine months instead of two years (ideally) or at least one whole year, to cover once or twice the seasonal cycle. Multitemporal interferometry was produced with two techniques and nominal spatial analysis of 2 x 2 m for the ascending and descending orbital geometries. They were corrected geometrically and quantitatively and plotted on maps. The corner reflectors placed before the acquisitions were used as stable measuring points.

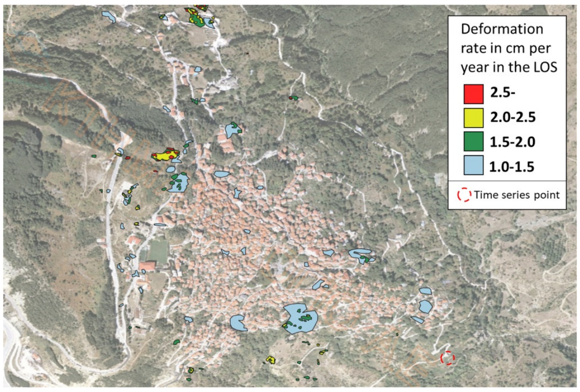


Figure 11. Polygons with all the deformation rate ranges of the DS of the descending track. With red dashed circle is marked the point that its time series is presented in Figure 12.

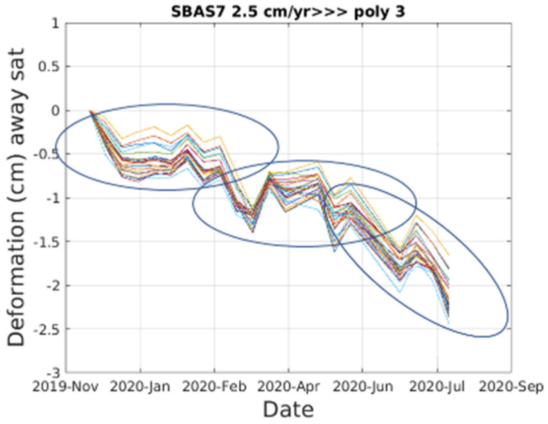


Figure 12. Characteristic time-series of deformation of a DS. Two sudden outbursts can be discriminated, in February and May 2020 with a constant deformation rate after June 2020. The location of the point is shown in Figure11.

No failure of large importance and extension was observed for the studying time, apart from some focused or minor failures. In addition, small-width deformations were found in a set in moderate extended area ENE and SW within Metsovo with an order of magnitude approximately 5 mm/year. Eleven locations were detected with a very small spatial extension with deformation of about 1-2 cm/year and with a small spatial extension and values of about 1-1.5 cm/year. Five of these sites focus on the area where the inclinometers and a GNSS receiver were installed. In this area, apart from the focused deformations, there are indications of failure of the slope in SW of the corner reflector and inside and around it in the location of the corner reflector and positions ‘d’ and ‘e’.

More detailed mapping (in larger scale) of the deformation rates (from InSAR producst) were performed, resulting in the creation of vector files (polygons), by grouping the deformation rates into four groups, providing, also, the deformation time series. According to this, the deformation rates in the largest spatially landslide is 1-2 cm/year. Compared with the detected rate of 4-16 mm/year of the subsurface ground movement as it has been recorded with the use of inclinometer probes leads to the conclusion that multitemporal interferometry and inclinometer results are in a good correlation, since the effect of the subsurface ground movement is visible on the surface with the use of MTInSAR.

However, detectable deformations are of slow deformation, which are limited in time during the period of satellite receptions. No information can be provided before or after the acquisition period but only possible sources of future failures, some of them characterized as precursors. Their persisting deformation in future monitoring studies, strengthen their characterization as such. The continuation of the monitoring, even at a lower spatial resolution, on an operational basis to monitor the evolution or detection of new slow displacements will be an investment to avoid large-scale failures with multiple costs, comparing to the monitoring ones.

Concerning the UAV campaigns proved to be an efficient tool for surface landslide small movement mapping. It is characteristic that small surface changes and altitude changes directly related to the landslide were recorded in the schoolyard of Zotiko. It was turned out that the cracks in the schoolyard are expanding. The comparative study of the DSMs confirmed a vertical surface deformation of 2 cm in some places within the period 2018-2020. This deformation is the effect of the recorded with inclinometer probes subsurface horizontal movement rate of 10 mm/year. This leads to the conclusion that the subsurface horizontal movement of 10mm/year in the depth of 14 m affects the whole area of the schoolyard, and the result in the surface is a vertical deformation of 2mm.

VIII. CONCLUSIONS

The landslide study areas of Metsovo and Zotiko are typical examples of complex landslides, which are usually exist in Western Greece. In both areas landslides have been involved mainly in the weathered flysch and are still active with extremely slow movements.

The short and long-term monitoring is carried out with the use of a complete system consisting of geotechnical, meteorological and GNSS instrumentation as well as UAV and MTInSAR.

The obtained results of the system measurements are positively correlated, especially the combination among multitemporal interferometry, UAV and inclinometer readings. Concerning the GNSS receivers it seems that they need more time to get more realistic measurements. According to Carlà *et al*. (2019) realistic results about landslides need at least four years of processed GNSS data.

Depountis *et al.* (2021), proposed that results from such a system may appear in real-time through a specially designed internet platform (WebGIS) and this could constitute a powerful tool for the local authorities in case of emergency. The combination of short- and long-term monitoring of the parameters connected to the landslide activity and kinematics, with the results presented efficiently in a WebGIS is the next step of this research, for the operation of the presented system as a Landslide Early Warning System (LEWS).

IX. ACKNOWLEDGEMENTS

This research was funded by the Regional Operation Programme Epirus 2014-2020. We would also like to acknowledge Deutsches Zentrum für Luft und Raumfahrt (DLR) to provide the TERRASAR-X satellite acquisitions within the science project GEO3659 as well as the TREE company for providing the data of the GNSS station GARD of the URANUS network.

References

Berardino, P., Fornaro, G., Lanari, R., and Sansosti, E. (2002). A new algorithm for surface deformation monitoring based on small baseline differential SAR interferograms. *IEEE Transactions on Geoscience and Remote Sensing,* 40(11), pp. 2375–2383.

Carlà, T., Tofani, V., Lombardi, L., Raspini, F., Bianchini, S., Bertolo, D., Thuegaz, P., and Casagli, N. (2019). Combination of GNSS, satellite InSAR, and GBInSAR remote sensing monitoring to improve the understanding of a large landslide in high alpine environment. *Geomorphology,* Vol.35, pp. 62-75. DOI: 10.1016/j.geomorph.2019.03.014.

Casu, F., Manzo, M., and Lanari R. (2006). A quantitative assessment of the SBAS algorithm performance for surface deformation retrieval from DInSAR data. *Remote Sens. Environ.,* 102(3/4), pp. 195 -210.

Depountis, N., Sabatakakis, N., Kavoura, K., Nikolakopoulos, K., Elias, P., and Drakaos, G. (2021). Establishment of an integrated landslide early warning and monitoring system in populated areas. In: *Understanding and Reducing Landslide Disaster Risk.* Casagli N. et al. (eds), Vol.3, pp. 189-194. ISBN 978-3-030-60311-3.

Eltner, A., and Sofia, G. (2020). Structure from motion photogrammetric technique. In: *Developments in Earth Surface Processes.* Tarolli P. et al. (eds), Vol.23, pp. 1-24.

Ferretti, A., Fumagalli, A., Novali, F., Prati, C., Rocca, F., and Rucci, A. (2011). A New Algorithm for Processing Interferometric Data-Stacks: SqueeSAR. *IEEE Transactions on Geoscience and Remote Sensing,* 49(9), pp. 3460-3470.

Kavoura K, Konstantopoulou M, Depountis N, and Sabatakakis N (2020). Slow-moving landslides: kinematic analysis and movement evolution modelling *Environmental Earth Sciences,* 79:130, 11. DOI: 10.1007/s12665-020-8879-7.

Koeva, M., Muneza, M., Gevaert, C., Gerke, M., and Nex, F. (2018). Using UAVs for map creation and updating. A case study in Rwanda. *Surv. Rev.,* 50, pp. 312–325. DOI: 10.1080/00396265.2016.1268756.

Kyriou, A., Nikolakopoulos, K., Koukouvelas, I., and Lampropoulou, P. (2021a). Repeated UAV Campaigns, GNSS Measurements, GIS, and Petrographic Analyses for Landslide Mapping and Monitoring. *Minerals,* 11, 300. DOI: 10.3390/min11030300.

Kyriou, A., Nikolakopoulos, K., and Koukouvelas, I. (2021b). How Image Acquisition Geometry of UAV Campaigns Affects the Derived Products and Their Accuracy in Areas with Complex Geomorphology. ISPRS *International Journal of Geo-Information,* 10(6):408. DOI: 10.3390/ijgi10060408.

Lainas, S., Depountis, N., and Sabatakakis, N. (2021). Preliminary Forecasting of Rainfall-Induced Shallow Landslides in the Wildfire Burned Areas of Western Greece. *Land,* 10, 877. DOI: 10.3390/land10080877.

Leick, A. (2004). GPS satellite surveying. Hoboken (NJ), John Wiley & Sons.

Mancini, F., Dubbini, M., Gattelli, M., Stecchi, F., Fabbri, S., and Gabbianelli, G. (2013). Using Unmanned Aerial Vehicles (UAV) for High-Resolution Reconstruction of Topography: The Structure from Motion Approach on Coastal Environments. *Remote Sens.,* 5, 6880–6898. DOI: 10.3390/rs5126880.

Micheletti, N., Chandler, J., and Lane, S.N. (2015). Structure from motion (SFM) photogrammetry. *Geomorphological Techniques,* Chap. 2, British Society for Geomorphology.

Nikolakopoulos, K.G., Soura, K., Koukouvelas, I.K., and Argyropoulos, N.G. (2017a). UAV vs. classical aerial photogrammetry for archaeological studies. *J. Arch. Sci. Rep.,* 14, pp. 758–773. DOI: 10.1016/j.jasrep.2016.09.004.

Nikolakopoulos, K.G., Kavoura, K., Depountis, N., Kyriou, A., Argyropoulos, N., Koukouvelas, I., and Sabatakakis, N. (2017b). Preliminary results from active landslide monitoring using multidisciplinary surveys. *European Journal of Remote Sensing,* 50:1, pp. 280-299. DOI: 10.1080/22797254.2017.1324741.

Rahmat-Samii, Y. (2007). Antenna Engineering Handbook, Chap. 15–43 (Reflector Antennas). New York, NY: McGraw-Hill.

RINEX (2014). The Receiver Independent Exchange Format Version 3.02, page 38, web.archive.org. International GNSS Service (IGS). 18 October 2014. Retrieved 30 May 2019.

Westoby, M.J., Brasington, J., Glasser, N.F., Hambrey, M.J., and Reynolds, J.M. (2012). 'Structure-from-Motion' photogrammetry: A low-cost, effective tool for geoscience applications. *Geomorphology,* 179, pp. 300-314.

WP/WLI (1995). A suggested Method For Describing the Rate of Movement of a Landslide. International Geotechnical Societies. In: *UNESCO Working Party on World Landslides Inventory, Working group on Rate of Movement*. Bonnard C. (ch), Bull. IAEG, 52, pp. 72-78.