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Deformation analysis in landslides NE Bulgaria using GNSS data complemented by InSAR for better interpretation results

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ABSTRACT

The Bulgarian northern Black Sea coast is affected by many landslides. Landslide research is important as these phenomena cause loss of human lives and infrastructural damages. For this study a landslide area called "Dalgiya yar" was selected. The objective of this study is to provide solid grounds for monitoring the landslide processes using GNSS and SAR data. To achieve the set goals a geodynamic network was established. Those networks consist generally of two types of points – reference (located on geologically stable terrain) and survey points located within the landslide. The overall deformation analysis of the geodynamic networks is done after the third measurement cycle. The main approach to obtain the final results is based on determination of deformation components of spatially oriented triangles. For the studied period and for the mentioned area three main types of deformations have been determined by Finite Elements Method – station displacements, relative side deformations and relative principal deformations. It needs to be mentioned that due to peculiarities of the researched zone the condition that the final elements must to be configured approximately as equilateral triangles with approximately equal areas and not overlapping was not possible to be met. This is the reason to complement the GNNS results with such produced by DInSAR processing of Sentinel-1 data for the mentioned periods.

I. Introduction

The development of contemporary geodetic techniques and its combination remote sensing is a sufficient prerequisite for getting more detailed, comprehensive and accurate information on the dynamic behavior of the earth's crust. In this case it is essential to underline the need to guarantee the most complete and accurate information that reflects the peculiarities of the Earth dynamics. This information will be achieved using GNSS data from local and continuously operating reference stations (CORS) networks complemented by freely available SAR data from the Copernicus program. In this study the authors propose that the data from the stable points to be provided by continuously operating reference stations National GNSS network. On the other hand local survey points in the studied landslide which consist of a total of 30 points were measured in static mode in three consecutive cycles in the period June 2019-2021. The main axes of deformation are determined by Methods for determining the deformation components of spatially oriented triangles. Graphic analysis was made and comparison of the results obtained and justified is the need for regular monitoring of landslides processes registering the ongoing surface movements and changes in the landslides body.

II. Research areas

The study area "Dalgiya yar" is a landslide circus located in the Varna landslide region, which includes the coastline that begins at north of Varna town and reaches the valley of the river Batova, near the village of Kranevo. The formation of deep landslides in this area is mainly due to sea abrasion. These are large landslide complexes of circus type found on the eastern slope of the Frangen plateau - from its edge to the beach. Besides these old stabilized landslides being result of the complex impact of natural factors and man-made activity, modern active local landslides are emerge as well (Bruchev *et al.,* 2007; Evlogiev and Evstatiev, 2011). In the mentioned study area of "Dalgiya yar" included are several active landslides which boundaries overlap and therefore are difficult to distinguish from one another. Even for some of the studied landslides located in this area, a smaller landslide can be located inside them. The "Fara" landslide filed under the identification number VAR 02.54145-01-17 in the register of landslides of the Republic of Bulgaria, that is located between the village of Kranevo and the tourist resort "Panorama" and covers only the lower steps of the circus "Dalgiya yar" has activated on 13 October 2012 destroying the lighthouse and the villas around it.

III. GNSS NETWORK

A. *GNSS permanent network*

In this research specific method for monitoring the deformations of the landslide processes using GNSS technology has been proposed. It is based on data from two types of GNSS networks - reference CORS stations located on geologically stable terrain and points located in the landslide body that forms a local geodetic network. Data for the stable points located in non-deformable zones in the investigated region are provided by the stations from the permanent National GNSS network (Georgiev *et al*., 2020) maintained and pre-processed by NIGGG-BAS (see Figure 1).

Figure 1. Stations from national permanent geodetic network (red triangles).

All measurements from the local geodetic network are processed and analyzed using data from the CORS points located the research area. In this study long-term processing of data from continuously operating reference stations is performed to obtain the coordinates and velocities of the stations, because this also affects the local geodetic network built established for studying the landslide area.

It needs to be pointed out that the velocities of the points from the National GNSS network in the northern Black Sea region are relatively small, less than 1 mm/year (Geogiev *et al.*, 2020) while for other regions of territory of Bulgaria they can reach 3-4 mm/year. To obtain the movements of the points from the local geodynamic networks, it is possible to process their GNSS measurements together with the GNSS measurements from the points of National GNSS network but the velocities of the CORS station must be taken in to account as well (Atanasova *et al*., 2021).

B. *Local geodetic network*

For this specific study a local GNSS network covering the landslide area "Dalgiya yar" (see Figure 2) was established. It consists of a total 30 stabilized points with some being metal pipes 35 cm long while other are metal bolts nailed in the stable rocks. In the mentioned geodynamic network "Dalgiya yar" previously points used for GNSS measurements in the network used to monitor deformations along the road above the landslide are included were found on the ground and used too (see Figure 2).

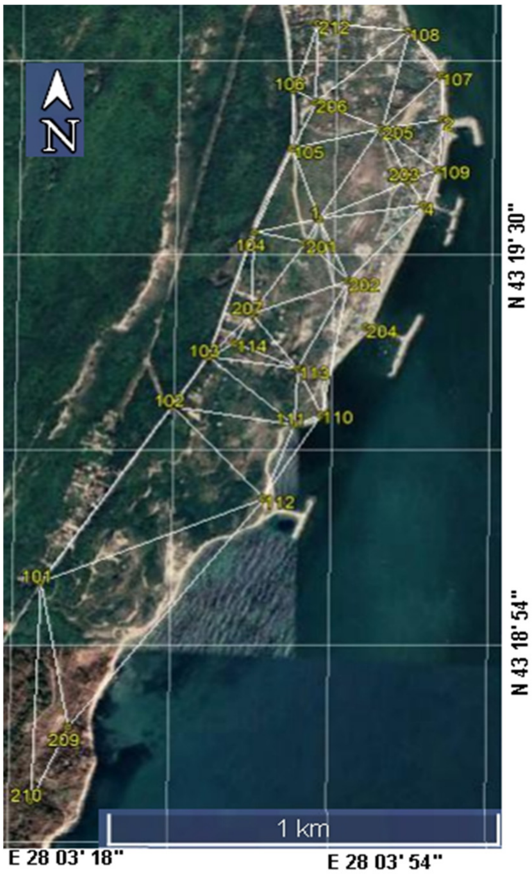

Figure 2. Local GNSS geodetic network at Dalgiya yar.

The GNSS measurements were carried with 2 receivers of type CHC i80 with horizontal precision 2.5 mm + 0.1 ppm RMS and vertical 3.5 mm + 0.4 ppm RMS and 1 receiver - P3E GNSS sensor used as reference station. Static mode with an interval 1 sec. and duration of one hour was applied for the GNSS measurements The results of the GNSS measurements were processed using "CHC Geomatics Office 2" software in the coordinate system WGS84. This newly established geodynamic network located inside the landslide area was measured once a year. The first measurement cycle of the geodynamic network was carried out in June 19-23 2019, second in June 22-27 2020 and the third cycle was measured in June 21-28 2021. The deformation analysis of the geodynamic networks was done after the third measurement cycle. Points 0204, 0208, 0211 were destroyed after the first cycle and no measurements were made thereafter.

To approximate the velocities linear regression model was used. During processing it can be selected whether all measurements from all epochs should be included in further calculations or those exhibiting strong deviation should be removed. The spatial coordinates X, Y, Z, are transformed into local coordinates with components north N, east E and up U while the epoch 2019.4658 is considered zero. In this case the increase along the northern (eastern) component is determined and the coordinates of the point for each subsequent epoch are reduced by the values of the coordinates from the zero epoch. The abscissa graphically shows the increase along the northern (eastern) component and along the ordinate the time intervals. Approximate the value of the velocity as a linear function (linear regression) Figure 3 show the approximation of the velocity values along the northern and eastern components for point 102, the approach is analogous for the other 30 points of the network.

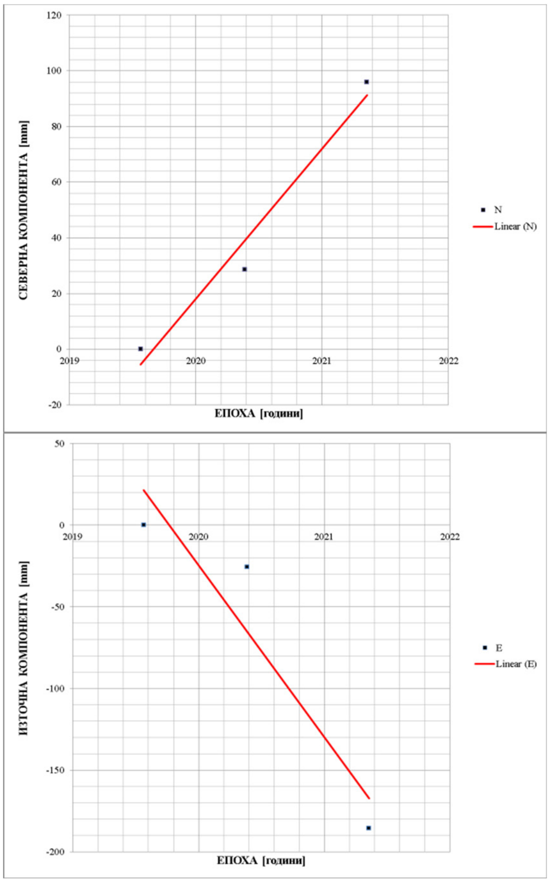

Figure 3. Determination of velocity by a linear regression along the north and eastern component for each point of the local geodetic network.

Displacements of local GNSS points (located in the body of the landslide circus) calculated by between epochs 2019-2021 (between the first and second, second and third and first and third cycles) are based on the coordinates adjustment for each cycle and are presented in Figure 4 for the northern, east and up components. The 2D magnitude of the displacement vector for each point of the local network was calculated too.

For the majority of geodetic studies the finite element model (FEM) is mainly used in the analysis of movements of stations based on results from GNSS data processing in order to obtain the strain tensors and strain accumulation (Bogusz *et al.*, 2013; Vassileva and Valev, 2015; Vassileva and Atanasova, 2017). More details on theory of the developed method has been presented in (Vassileva *et al.*, 2017).

	2020-2019		[mm]		2021-2019		[mm]		2021-2020		[mm]	
ID	n	e	h	2D	n	e	u	2D	n	e	u	2D
1	12.6	4.2	32.1	13.3	4	2.4	21.5	4.66	-8.6	-1.8	-10.6	8.79
2	1.8	16.1	2.8	16.2	1.3	16.7	8.4	16.8	-0.5	0.6	5.6	0.78
4	-15.9	12.6	-24.6	20.3	-13.5	20.4	63.9	24.5	2.4	7.8	88.5	8.16
101	-13.5	15.6	0.5	20.6	-19.4	34	3.2	39.1	-5.9	18.4	2.7	19.3
102	-28.5	25.1	24.2	38	-95.9	18.6	93.7	209	-67	160.5	69.5	174
103	-20.2	20.2	34.5	28.6	-28.2	53.1	21	60.1	-8	32.9	-13.5	33.9
104	-14.1	5.5	27	15.1	-21.3	-9.3	25.3	23.2	-7.2	-14.8	-1.7	16.5
105	-8.3	7.4	-4.3	11.1	-6.1	-9	14.9	10.9	2.2	-16.4	19.2	16.5
106	-2.7	0.1	-0.7	2.7	5.6	-24.8	24	25.4	8.3	-24.9	24.7	26.2
107	10.6	10.7	-3.4	15.1	10.8	6.3	24	12.5	0.2	-4.4	27.4	4.4
108	5.2	8.9	0.1	10.3	16.4	2	10.8	16.5	11	-6.9	10.7	13.2
109	8.1	-3.8	-60	8.95	13	-1	-5.1	13	4.9	2.8	54.9	5.64
110	-14.4	69.9	80.6	15.9	-15.4	10.7	87.4	18.7	-9.9	37.4	6.8	38.7
111	-21.2	5.7	-22	22	-11.3	24.3	32.6	26.8	9.9	18.6	54.6	21.1
112	-7.6	2	17.7	7.86	21	15.6	59.2	26.2	29	13.6	41.5	31.7
113	-23.3	16.4	31.6	28.5	-24.4	39.9	41.3	46.8	-1.1	23.5	9.7	23.5
114	8.3	12.8	-24	15.3	1.9	6.2	5.3	6.48	-6.4	-6.6	29.3	9.19
201	1	1.5	15.1	1.8	-9.4	3	32	9.87	-10	1.5	16.9	10.5
202	-5	2.9	12.7	5.78	-14.3	-1.1	26.4	14.3	-9.3	-4	13.7	10.1
203	3.4	3.5	17.1	4.88	8.3	-0.7	33.7	8.33	4.9	-4.2	16.6	6.45
205	-15.9	-14.8	24.2	21.7	-41	55.1	90.9	68.7	-25	69.9	66.7	74.3
206	2	-6.1	4.7	6.42	-5.9	3.9	32.2	7.07	-7.9	10	27.5	12.7
207	-18.1	4.7	40.1	18.7	-4.2	5.2	42.9	6.68	14	0.5	28.1	13.9
209	11	24.9	-50.3	27.2	54.8	34.2	-50	64.6	44	9.3	0.2	44.8
210	-21	-17.26	-21.4	17.4	-21.1	-17.4	-22	17.6	-0.6	-17.1	-24.3	17.1
212	-11.3	-1.5	37.1	11.4	-11.9	15.3	51.5	19.4	-0.6	16.8	14.4	16.8

Figure 4. Displacements for the points from the local GNSS network calculated for epochs 2019-2021.

Common practice is the use of reduced (to the surface of a reference ellipsoid or in a map projection) geodetic measurements. Such an approach, which is imperatively applicable in regular geodesy leads to significant manipulation (inaccuracies) of the deformation model. The main reasons for such a statement are the following: the reduced geodetically determined elements (most often distance) on the reference ellipsoid are directly dependent on the ellipsoidal heights of the defining points. It is not considered that it is quite possible that sections with different heights are actually subject to the deformation processes having same intensity. As it is known the length of the reduced baseline depends on the parameters of the selected reference ellipsoid. The length of the distance in projection is definitely influenced by the distance of the main meridian (parallel). Thus, too often elements that have undergone deformations with purely geometric nature are used without these deformations being of geodynamic origin. Thereby, consciously or not, created is a manipulated deformation model with altered sensitivity and reliability. It needs mentioning that there are various geodetic methods that are used to determine the displacements of points on the earth's surface covering fixed period of time caused by activation of various geodynamic phenomena. Those displacements are related to the selection of a fixed origin used coordinate system. It should be underlined that absolutely fixed points on the earth's surface do not exist - so the movements themselves are to some extent quite relative. Therefore, it is more appropriate to base the analysis of the studied geodynamic phenomena on elements independent of the coordinate origin – baselines. Baselines whose deformations in time will be the basis for determining the main deformation components of the studied object in two main ways are determined; by the coordinates of their endpoints and by direct measurement of the baselines. The direct determination of the lengths of the chords in space is in-line with the most accurate and modern geodetic methods (GNSS, Laser scanners, LIDAR). This is an additional advantage in the implementation of this method. In this study the adopted strategy is to study the deformation processes through the use spatial chords based on geodetic measurements, based on the theory of deformation and the FEM. Extract of baselines are presented in Table 2.

Table 2. Extract of baselines (Ellipsoid Distance) on geodetic measurements, between epochs 2019-2021

Baseline ID	2019	2020	2021
0001->0203	255.3331	255.3306	255.3326
0001->0202	196.0049	196.0235	196.0192
0001->0201	75.4893	75.5011	75.5091
0001->0205	304.7517	304.7176	304.7179
0001->0206	337.2371	337.2221	337.2279
0001->0105	217.2407	217.2401	217.2343
0001->0106	378.8347	378.8397	378.8419
0002->0107	128.0989	128.1059	128.1179
0002->0108	270.0403	270.052	270.0633
0002->0109	144.131	144.1192	144.1143
0002->0207	741.9788	742.0012	742.0229
0111->0004	699.9488	699.9462	699.9451
112->0004	929.0988	929.0588	929.0694
0113->0004	567.9632	567.96	567.9611

Below shown are the results from using results periodic measurements on which calculated are the components of deformation in the region of the landslide. This is considered as possibility to study the deformation processes through the use of measured parameters – spatial chords based on geodetic measurements carried out based on the theory of deformations and FEM. Calculated were the spatial chords between the points that cover the main structures in the area of the specific landslides (geodynamic) areas using the results from GNSS measurements for the epochs 2019, 2020 and 2021.

As basis for calculation used is the well-known formula (Toshev, 1967) that gives the relationships between the components of deformation tensor and the linear deformation of a section of a deformation environment. For each of the triangles composed and determined is a system of three equations as a result of which the received tensor components of a "pure" deformation. Calculated are the major axes of relative deformation to the median’s center of the triangle too. All these elements characterize the deformation processes reduced to the plane of the respective triangle. Graphical representations of the major axes of deformation are given in Figure 3. The results of GNSS measurements for the period 2019 - 2021 were used, on the basis of which the baselines were calculated between the points (Figure 3).

C. *Relative principle deformations*

The relative principal deformations of each finite element are obtained and they are shown in Figure 5 (compression in blue and extension in red). Relative principal deformations of finite elements in the areas in the circus reveals that during the studied time period the movements are dominantly of extension ranging from 0.5 mm up to 30 mm and the directions are mainly west-east. In the maps shown are the extensions in the north part and in the south part of the landslide circus which are approximately of the same magnitude.

The relationship between directions of the principal deformations of each finite element and the directions of its side deformations are very close. Directions of the principal deformations of extension or compression of every finite element dominantly are defined by the type of deformations of the sides of the respective finite element (Vassileva *et al.*, 2017). The obtained results for the principal deformations in this study confirm this relation (Figure 5).

IV. DInSAR processing of Sentinel-1

As noted above it needs to be mentioned that due to peculiarities of the researched zone the condition that the finite elements must configured approximately as equilateral triangles with approximately equal areas and thus the requirement for not overlapping was not possible to be met. This is the reason why is was necessary to complement the GNNS results with such produced by DInSAR processing of Sentinel-1 (S-1) data for the mentioned periods.

The color-coded earth displacements in LOS calculated from the phase signal for several periods by processing S-1 data are shown on Figure 6. The time period covers 4 months for the winter months starting in November 2015 up to March 2020. As it can be seen the calculated displacements are in the range between 30 mm (uplift) and -50 mm (subsidence). The obtained IFIs reveal that the registered deformations are concentrated in some local areas with uneven structure. A map of the concentration of deformations of the earth's crust was created from them. The pixels having coherence values below 0.3 in each IFI have been removed because they are considered unreliable.

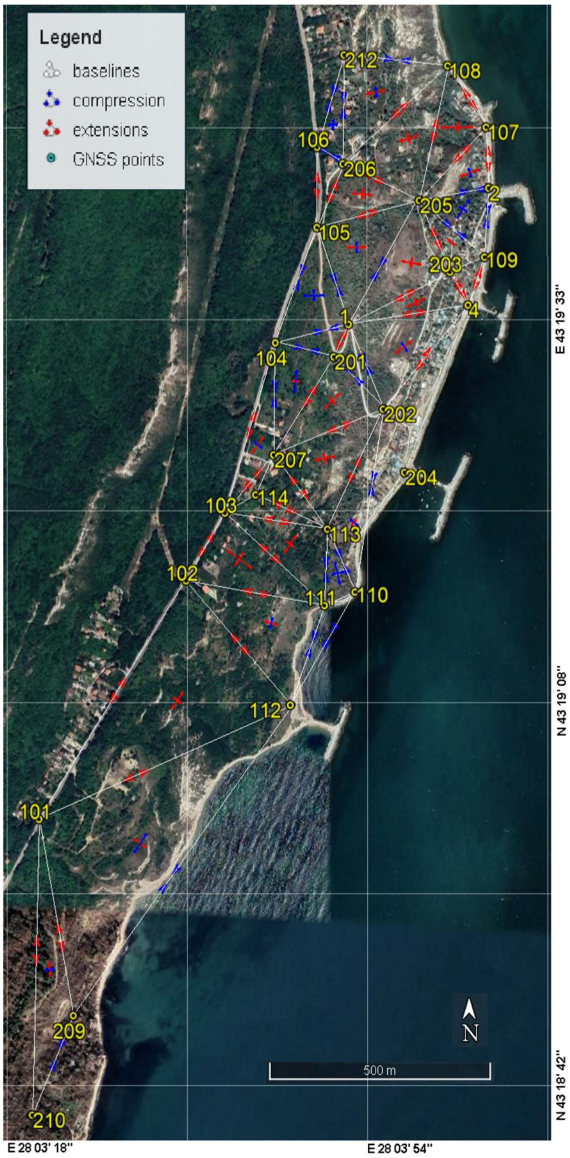

Figure 5. Relative side and principal deformations for the time span 2019-2021 (red vectors- extensions; blue vectors compression). Main axes of relative deformation to the median's center of the triangles.

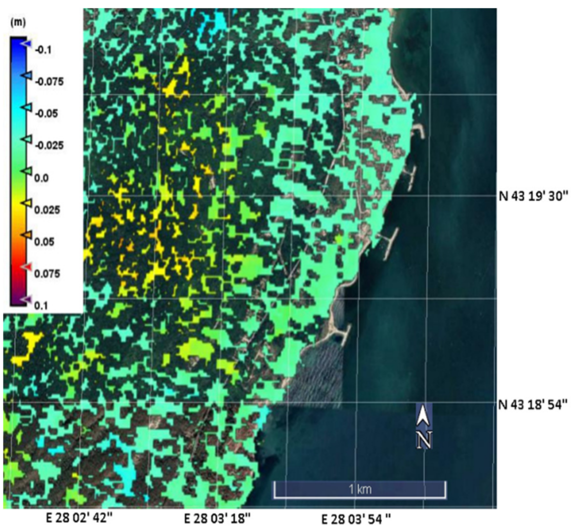

Figure 6. Case of application of the DInSAR research method for the "Dalgiya Yar" landslide: surface displacement maps 29Nov2019_28Mar2020.

The color of the pixels represents the movement of the surface in the meter units for the studied period, ranging from dark blue to purple (Atanasova *et al.*, 2021). The most vulnerable areas are shown in purple and less vulnerable ones are in yellow and green, but our the case is prevailing from yellow to light blue. The area enclosed by the polygon of geodetic points 208, 209, 101, 102, 111 and 112 (see Figures 5 and 6) is inaccessible because it is on steep slope with high inclination. These points were not monitored by GNSS measurements during the campaigns (Atanasova *et al.*, 2019; Dimitrov *et al.*, 2020). It is worth noting that the earth surface movements in this area are monitored only by SAR data and have some of the most significant subsidence values for the studied period. The maps portraying the mean surface displacements in the LOS direction are shown on Figure 6. The research approach applied demonstrates the potential and ability of DInSAR to study and monitor landslides and measure their trend in LOS with centimetre accuracy over time using freely available data and software for such inaccessible areas. For monitoring the ground deformation, due to the relativity of the DInSAR technique, other types of measurements such as GNSS, precise levelling, and UAS or LiDAR are needed to supplement the data from the satellite remote sensing.

V. Conclusion

The results of study showed that registered motions on the Earth's crust in the area are reliable. They also confirmed that the GNSS and InSAR methods used are appropriate for determining the induced surface movements. Provided are major conclusions about the nature of the deformation processes and the possible status of their development. The results from the geodetic monitoring of the deformation in the landslide region allow conclusions to be drawn with regard to the local deformations that are taking place of the ground surface. These deformation processes could be explained with concentration of the landslide developments the region. The question stays open whether local movements or the induced anthropogenic ones prevail. For clarifying this issue needed is new deep and complex approach including modern interpretation of the results using geological information as well.

VI. Acknowledgements

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