Application of SBAS-DInSAR to monitoring landslides along the northern Black Sea coast in Bulgaria

M Yamaguchi¹, P E Yastika², N Shimizu³, N Milev⁴ and I Vrkljan⁵

¹Nippon Koei Co., Ltd., Tokyo, Japan
²University of Mahasaraswati Denpasar, Bali, Indonesia
³Yamaguchi University, Ube, Japan
⁴University of Architecture, Civil Engineering and Geodesy, Sofia, Bulgaria
⁵University of Rijeka, Croatia

nshimizu@yamaguchi-u.ac.jp

Abstract. The Black Sea coast of Bulgaria is well known as an active landslide area across which various landslides extend. Monitoring the real behavior of landslides has not often been conducted due to technical difficulties and cost issues, although it is essential to reveal the mechanism of these landslides and to solve the problems they cause. In this paper, SBAS-DInSAR is applied to monitor the landslide displacements along the northern Black Sea coast. The results are compared with the field observation results described in the official annual reports of landslides issued in Bulgaria and other published papers. It is found that the SBAS-DInSAR results show a good agreement with the actual behavior and verify its applicability for monitoring landslides in extensive areas along the northern Black Sea coast.

1. Introduction

The Black Sea coast of Bulgaria is well known as an active landslide area across which various landslides extend [1]. A lot of research has been done from geological and engineering viewpoints, and some countermeasure works have been performed for stabilizing the landslide behavior and protecting people’s lives and properties. On the other hand, monitoring the real behavior of landslides has not often been conducted due to technical difficulties and cost issues, although it is essential to reveal the mechanism of these landslides and to solve the problems they cause.

Differential Interferometric Synthetic Aperture Radar (DInSAR) [2] has the potential to be an efficient, effective, and economical method for monitoring the landslide behavior in this extensive area. With this method, it is possible to measure the ground surface displacements with the accuracy of a few centimeters or less from satellite data taken more than 500 to 700 km away from the Earth’s surface. The accuracy can be improved by the temporal analysis of the Small Baseline Subset (SBAS) or Permanent Scatters (PS) DInSAR using a large amount of satellite data. The other advantages of DInSAR are that it can monitor extensive areas without the use of any sensors on the ground surface. Actually, DInSAR has already been applied to this area to observe the displacement distribution [3], [4].

In this paper, SBAS-DInSAR [5] is applied to monitor the landslide displacements in the Balchik and Kavarna area, along the northern Black Sea coast, and the results of SBAS are compared with the actual ground behavior described in the official annual report of landslides in Bulgaria [6] in order to confirm the validity of the method.
2. Outline of SBAS-DInSAR

Synthetic Aperture Radar (SAR) is a high-resolution radar device (e.g., 10 m x 10 m) that is mounted on an aircraft or artificial satellite. It can be used efficiently even at night and under any weather conditions. Interferometric SAR (InSAR) is a method for taking the signal phase difference from two scenes of SAR data, which are observed in the same area at different times. DInSAR is a technique for measuring the displacements of the Earth’s surface based on the same process as that of InSAR [2].

The Small Baseline Subset (SBAS) method [5] enables the reduction of phase noises and errors from many interferograms. It is capable of isolating only the phases that were contributed by the deformation.

The SAR satellite travels on ascending (northward) and descending (southward) orbits (figure 1) and observes the displacement in the Line of Sight (LOS) direction along the radar beam's line (figure 2).

3. Study area and SAR data set

3.1. Study area

Figure 3 shows the distribution of landslide locations at Balchik and Kavarna along the Black Sea coast in northern Bulgaria [7]. In this region, there are four landslide hotspots, namely, Topola village, Alley Echo (EXO), Sviloza, and Fish-Fish, which are represented by the squared regions in the figure. Topola village and Fish-Fish are discussed in this paper.

Figure 4 is a geological map with the landslides along the northern Black Sea coast [8]. The regions denoted by “V” and “IV” along the coast represent the target areas including Topola village and Fish-Fish, respectively. These regions are composed of limestone (kvN1), aragonite clay with limestone interaction (toN1), and diatomaceous clay (evN1kg-s) [8].

3.2. Data collection and SBAS-DInSAR processing

In this study, the Sentinel-1A/B data are used to create the interferogram for the DInSAR analysis. Two datasets, namely, 273 scenes on the descending pass observed from 8 October 2014 to 9 May 2020, and 196 scenes on the ascending pass observed from 9 October 2014 to 7 September 2020, are used. The number of orbit paths for the descending data is 36, while that for the ascending data is 58.
All scenes are right-looking observation data. All the Sentinel data were provided free of charge by the European Space Agency (ESA).

The SBAS-DInSAR processing for the descending data and that for the ascending data were conducted separately. All the SAR data processing was conducted using Envi-SARscape 5.5.3. (Harris Geospatial Solutions, Inc.). Figure 5 presents connection graphs representing the pairs of SAR data for obtaining the interferograms, for which the temporal baseline and perpendicular baseline threshold are set at 36 days and 2% of the critical baseline length, respectively. The ascending data processing was divided into two batches due to the limited computer space since there are many data for the ascending orbit. The vertical and horizontal axes show the relative positions and the data acquisition dates, respectively. In each graph, the green points and the yellow point represent the SAR data and the reference (super master) data, respectively. The blue lines represent the pairs of interferograms.

![Connection graphs of descending and ascending data for SBAS-DInSAR.](image)

(a) Descending (2014–2020)  (b) Ascending (2014–2017)  (c) Ascending (2017–2020)

**Figure 5.** Connection graphs of descending and ascending data for SBAS-DInSAR.

4. Results and Discussion

4.1. Spatial distribution of LOS displacements

Figure 6 shows the LOS displacement distributions of the target area from 2014 to 2020 for the descending and ascending passes obtained by the SBAS-DInSAR analysis. The displacements are represented by the range in colors from red to blue denoting mm units from −200 mm to 200 mm. The red and blue colors mean negative (extension) and positive (compression) LOS displacements, respectively. In the area with low coherence below the threshold value, the results of the LOS displacements have been removed from the map.

To evaluate the results of SBAS-DInSAR and to discuss its applicability for monitoring the landslide behavior in the Balchik and Kavarna area, those results are compared with the field observation results. In this chapter, Topola village and Fish-Fish (see figure 3) are taken for comparison and discussion.

![LOS displacement distributions by SBAS-DInSAR.](image)

(a) Descending (8 Oct 2014 to 5 May 2020)  (b) Ascending (9 Oct 2014 to 7 Sept 2020)

**Figure 6.** LOS displacement distributions by SBAS-DInSAR.
4.2. Topola village

4.2.1. Past landslide activities
Topola village is located in the western part of Kavarna Municipality along the Black Sea coast (see figure 3). Along the coastline, the lower part of the landslide slope is composed of diatomaceous clay of the Euxinograd Formation (evN1[6*]), while the main part of the slope is composed of aragonite clay with limestone intercalations of the Topola Formation (toN1[5]). The northern part from the crown line of the main scarp comprises limestone of the Kavarna Formation (kvN1[5]), and the more northern area comprises loess (yellow soil) complex (colQ2). North of the crown line is a limestone plateau called the Lower Romanian Level (LRL) [8] (figure 4).

A landslide developed in the coastal area near a golf course around the eastern end of Topola village. Large deformation has been seen among the massive buildings located inside of the landslide area (figure 7 (a)). For example, one building is inclined backward and the front of it is visibly raised, while others have moved forward and are twisted [6]. This landslide was registered in 2014 as No. DOB 17.05009-01-03 [7]. The landslide has cut off the road to the golf course, and transverse ridges have appeared, as shown in figure 7 (b). There are terraces and cliffs at the landslide toe up to a height of about 3.0 to 4.0 m along the coastline. On the western side, near the coastal cliff, a scarp with preserved sediments and a sloping formation is visible. The scarp may have been affected by sea erosion [6].

![Small landslides indentation](image1)
![Boundary of the landslide DOB 17.05009-01-03 - tentatively](image2)

(a) Boundary of landslide

![Damaged buildings and transverse ridges (red line)](image3)

(b) Damaged buildings and transverse ridges (red line)

Figure 7. Landslide around eastern end of Topola village [6].

4.2.2. Results of SBAS-DInSAR and discussion
The LOS displacement distribution maps for the descending and ascending data around the eastern end of Topola village are shown in figure 8. SBAS-DInSAR detected large displacements in the eastern portion which are denoted by red, orange, and blue. Figure 9 shows the time-transition of the LOS displacements at four points (pixels) of interest (P29, P30, P31, and P33) in this area.

Point P29, on the plateau above the slope, is stable because almost no displacement appears, as shown in figure 9 (a). At P30, located in the area of the massive buildings (figure 7), both descending and ascending LOS displacements significantly increase toward the negative side (extension) with time (figure 9 (b)). Such behavior indicates that the actual displacement is dominantly subsidence. The eastern component of the displacement is estimated to be small. Since the slope faces south and the building sits on the middle terrace of the slope, the displacement is supposed to move in a southern and downward direction.

At P31, in the middle of the slope, the descending LOS displacement is almost zero or slightly positive, while the ascending one is negative (figure 9 (c)). This indicates that the actual displacement dominantly moves to the east and downward.
At P33, near the coastal area, both descending and ascending LOS displacements are compression, and the descending one is larger than the ascending one (figure 9 (d)). Therefore, the actual displacement seems to move upward and slightly to the east at the landslide toe.

From the above results, it is found that this area shows typical landslide behavior along the vertical section of P29-P30-P31-P33. The SBAS-DInSAR results correspond to the actual behavior described in the official report [6].

**Figure 8.** LOS displacement distributions around eastern end of Topola village.

**Figure 9.** Time transition of LOS displacements by ascending and descending data around eastern end of Topola village.
4.3. Fish-Fish area

4.3.1. Past landslide activities
The Fish-Fish area is located 3 km southwest of the town of Balchik. The “Fish-Fish east landslide” was registered in 1999 as No. DOB 03.02508-14. The active landslide, specifically named the “3rd and 4th street landslide”, was registered in 2000 as No. DOB 03.02508-14-2 [7] (figure 10).

The target landslide area mainly consists of diatomaceous clay of the Euxinograd Formation (evN3k[14]), while the southern part of the oldest landslide scarp consists of aragonite clay with limestone intercalations of the Topola Formation (toN1t). The northern part of the scarp comprises limestone of the Kavarna Formation (kvN3t), and its northern side is loess complex (eoIQh). Further north of the landslide crown line lies the limestone plateau (LRL) [8] shown in figure 4.

Around the boundary of three landslides, i.e., Fish-Fish east landslide, 3rd and 4th street landslide, and western Karamanlii landslide (figure 10 (a)), a few houses slid down in the landslide portion in 2015 and large damage was done to an outside wall (figure 10 (b)). In addition, numerous cracks and visible displacements were found along the road “Albena-Balchik”. These types of damage appeared repeatedly and the road had to be re-paved again and again from 2015 to 2019 [6].

![Figure 10. Landslides in Fish-Fish area [6].](image)

4.3.2. Results of SBAS-DInSAR and discussion
The LOS displacement distribution maps for the descending and ascending data around the Fish-Fish area are shown in figure 11. SBAS-DInSAR detected large displacements in the eastern portion which are denoted by red, orange, and blue. Points P1, P2, P3, and P5 are selected to show the time-transition of the LOS displacement. P1, located to the northwest away from the active landslide area, is stable because almost no displacement appeared, as shown in figure 12 (a).

At P2, located near the road Albena-Balchik, which has been continuously damaged, the ascending LOS displacement is negative, the descending one is positive, and the absolute value of the former one is larger than the latter (figure 12 (b)). Such behavior indicates that the actual displacement faces the east and downward. The eastern component of the displacement is estimated to be about 8 cm, and the slope faces the southeast. Therefore, the actual displacement seems to head to the east and downward toward the seacoast.

P3 and P5 are located in the sliding area and include a collapsed house. At P5, the descending and ascending LOS displacements significantly increase toward the positive and negative sides, respectively. Comparing the absolute values of the ascending and descending displacements, the ascending one is slightly larger than the descending one (figure 12 (d)). Such behavior indicates that
the actual displacement heads dominantly to the east. Since the slope faces the southeast, the actual displacement is supposed to move horizontally east to the sea and slightly downward. At P3, no ascending LOS displacement could be obtained due to the low coherence of the interferogram (figure 12 (c)). Considering the displacement distribution around P3, shown in figure 11 (b), the behavior at P3 could be estimated as being similar to that at P5.

From the above discussion, the SBAS-DInSAR results correspond to the actual behavior described in the official report [6].

Figure 11. LOS displacement distributions in “Fish-Fish” area.

Figure 12. Time transition of LOS displacements by ascending and descending data in Fish-Fish area.
5. Conclusions

In this study, the applicability of SBAS-DInSAR for monitoring the landslide behavior in the Balchik and Kavarna area along the northern Black Sea coast of Bulgaria was investigated by comparing the results of SBAS-DInSAR and the site observation results.

The distribution maps and the time-transition of the LOS displacements were obtained over a period of six years starting in 2014. SBAS-DInSAR was able to detect the typical landslide behavior in Topola village and the Fish-Fish area, which corresponded to the actual behavior described in the official report of landslides.

This study suggests that DInSAR will be a useful tool for long-term continuous landslide monitoring in the northern Black Sea coast.

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