Landslides
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Landslides at a uranium mill tailing deposit site Boršt (Slovenia) detected by radar interferometry

Abstract This paper presents a comparison of persistent scatterer interferometry (PSI) monitoring results with in situ displacement measurements at the November 1990 landslide at the Boršt uranium mill tailing deposit site after heavy rain. Although the landslide did not directly endanger people, site remediation works were undertaken due to the subsequent environmental problems. Additionally, in situ monitoring with benchmarks was established in order to detect the ground motion of the landslide body. PSI campaigning in the Škofjeloško-Cerkljansko area, where the uranium mill tailing is situated, performed for the purpose of measuring displacements of natural targets near the active landslide area, also detected displacements, most probably indicating a creeping process. When comparing the pre- and post-remediation velocities at the benchmarks located on the landslide with persistent scatterers (PSs) located near the landslide, the rates could be regarded as background. The results show that the remediation works in the form of a drainage tunnel were very effective as post-remediation velocities at the landslide closer to the PSs resembled the velocities of the PSs, while the velocities of the landslide mass above the drainage tunnel slowed down, even to below the background velocities. The high correlation values between the movements of the benchmarks and the PSs also confirm that the remediation works were effective as the fluctuations in the displacement values of the landslide were very similar to those of the PSs. Nevertheless, although there are several limitations in comparing the two different datasets, the PSI technique can be complementary to conventional in situ methods.

Keywords Uranium mill tailing deposit · Landslide · Radar interferometry · Persistent scatterers · Ground surveying · Slovenia

Introduction

Environmental degradation linked to the past or ongoing mining is a serious issue all over the world where past mining has occurred or contemporary mining still occurs, and Slovenia is no exception. As a result of the extensive exploitation of natural resources, and in particular of the mining and milling of uranium ores, large areas have become radioactively contaminated, necessitating restoration and/or appropriate land use management techniques to ensure that the health and safety of the affected population are not compromised.

During the 1980s and early 1990s, many older uranium mines were closed because of a decrease in the demand for uranium and an increase in the overall supply. The resulting low prices and the cost of providing the extra measures needed to satisfy society's higher expectations in the areas of environmental and radiological protection made production of uranium unprofitable for many low-grade mines. Some of the mines were large open-pits, but most were underground networks of shafts, caverns and tunnels, shored up by timbers. Because uranium milling and open-pit mining is conducted above ground, radon levels tend to be quite low, as radon is readily dispersed into the atmosphere. However, millers are exposed to uranium dust and thorium 230, both of which may have chemical or radiological toxicity, as well as to additional chemicals used in the extraction process. A side product of all mining is also mill tailing deposits that are dumped near the mining site. If the mill tailing deposits are not remediated properly, there is a strong possibility of consequential contamination of soils, surface water and groundwater in the vicinity of the deposit/tailing.

In the case of the Boršt mill tailing deposit site, more than half of the tailings were deposited on a fossil landslide which was reactivated in the early 1990s. Even though the landslide did not directly endanger people, the remediation works were undertaken due to the subsequent potential environmental problems. The landslide was stabilised in 1996 after the construction of a drainage tunnel in 1995. An interim cover made of material excavated from the tunnel was placed on the tailings pile to reduce radon emissions (Beguš et al. 2011).

The fact that landslides are a natural process and a very widely spread geohazard around the globe dictates a special approach towards minimising their effects on society. With this aim, a major effort in terms of landslide understanding, analysis and prediction is almost a necessity. Traditional methods used for mapping and monitoring slope mass movements (of which landslides are a part) can benefit from the application of remote-sensing techniques coupled with Geographical Information Systems (GIS) analysis. The use of remote-sensing technologies, whether airborne, satellite or ground-based (such as high-resolution optical or infrared imagery, satellite-based radar interferometric techniques, micro-satellite constellations and airborne and ground-based high-resolution methods) allows the rapid acquisition of quantitative data over wide areas, reducing the field work and consequently costs. The development of radar interferometric methods has enabled the efficient comparison of multiple radar imagery and a temporal data series of radar acquisitions over a longer period. Analyses of these series, also called persistent scatterer interferometry (PSI), have proven to be an efficient tool for monitoring subtle and slow deformations of the earth's surface (Colesanti and Wasowski 2006).

In this work, we focus on the landslide that occurred at the mill tailing deposit site on the Boršt hill after the cessation of uranium exploitation in 1990. The scope of the paper is to analyse and to compare the displacement rates from radar PSI techniques and conventional in situ measurements in the period from 1992 to 2001. The deformation rates of PSI were calculated parallel to the slope gradient (dipping) and compared with ground survey measurements.

Study area

The Boršt hill is the deposit site of uranium mill tailings, the secondary product of uranium concentrate production at the Žirovski vrh uranium mine. It is situated 45 km west of Ljubljana

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and 20 km west of Škofja Loka (46°05′7.36″ N, 14°10′53.38″ E) (Fig. 1). The area is part of the foothills of the Julian Alps. The site area extends over 4.2 ha and lies between 520 and 580 m a.s.l., 50 m above the Potoška ravine. The mill tailing disposal at Boršt covers the former water-rich ravine bottom.

Žirovski vrh is located at a wider junction of two great geotectonic units, the Outer Dinarides and the Southern Alps, which all belong to the Dinarides (Mlakar and Placer 2000). The area is built up of several extensive nappes originated from the time of Alpine orogeny. Nappes and thrust slices, oriented in the Dinaric and Alpine directions are dissected by numerous faults that run in the NW–SE, E–W and NE–SW directions.

In general, a wider area of the Žirovski vrh region consists mainly of Carboniferous and Permian clastic rocks (claystone, siltstone, sandstone, fine graded conglomerate) and carbonates (limestone), while Mesozoic strata consists of the clastic rocks (sandstone, siltstone, tuff) and carbonates (limestone and dolomite) (Fig. 1). Most commonly, fine graded to coarse Carboniferous and Permian clastic beds overlay the carbonate rocks (Mlakar and Placer 2000). The Boršt mill tailing deposit site is constituted of Upper Triassic–Carniolian clastic rocks with characteristic bedding of siltstone, sandstone and tuff beds. The general strata bedding dips towards NW with steep to very steep angles. Preliminary geology prospections found the whole Boršt area to be tectonically much damaged by and prone to shallow and deep landslides (Novak 1979). Also, additional detailed geological mapping in 2010 revealed several slope instabilities (Čar 2010). The whole area comprises of geologically controlled slides and deep seated gravitational slope deformations. The terrain is divided into several tectonic blocks, which they move independently of each other. Sub-vertical faults dissect the Carniolian rocks. The bedding of the strata is subparallel to the slope inclination and is, as such, very unfavourable with respect to stability.

Uranium mill tailing Boršt

Uranium deposits at Žirovski vrh were discovered in 1960. After feasibility studies and pre-exploitation activities were undertaken, the uranium mine Žirovski vrh was founded in 1976 and ore exploitation started in 1982. Uranium concentrate production, based on the acid procedure, started in 1984. During the mine's operational period, the Boršt location was being prepared in order to provide for the disposal of the uranium mill tailings. In 1990, the government of the Republic of Slovenia adopted a decision to stop extracting uranium concentrate (yellow cake) and the mine was closed in 1992, partly due to the political decision but largely due to the reduction in uranium demand and consequent to the lower market price of uranium.

During the pre-exploitation and exploitation period, over 60 km of tunnels were dug and over 380 km of percussion drilling was performed. In the same period, around 3,300,000 tonnes of

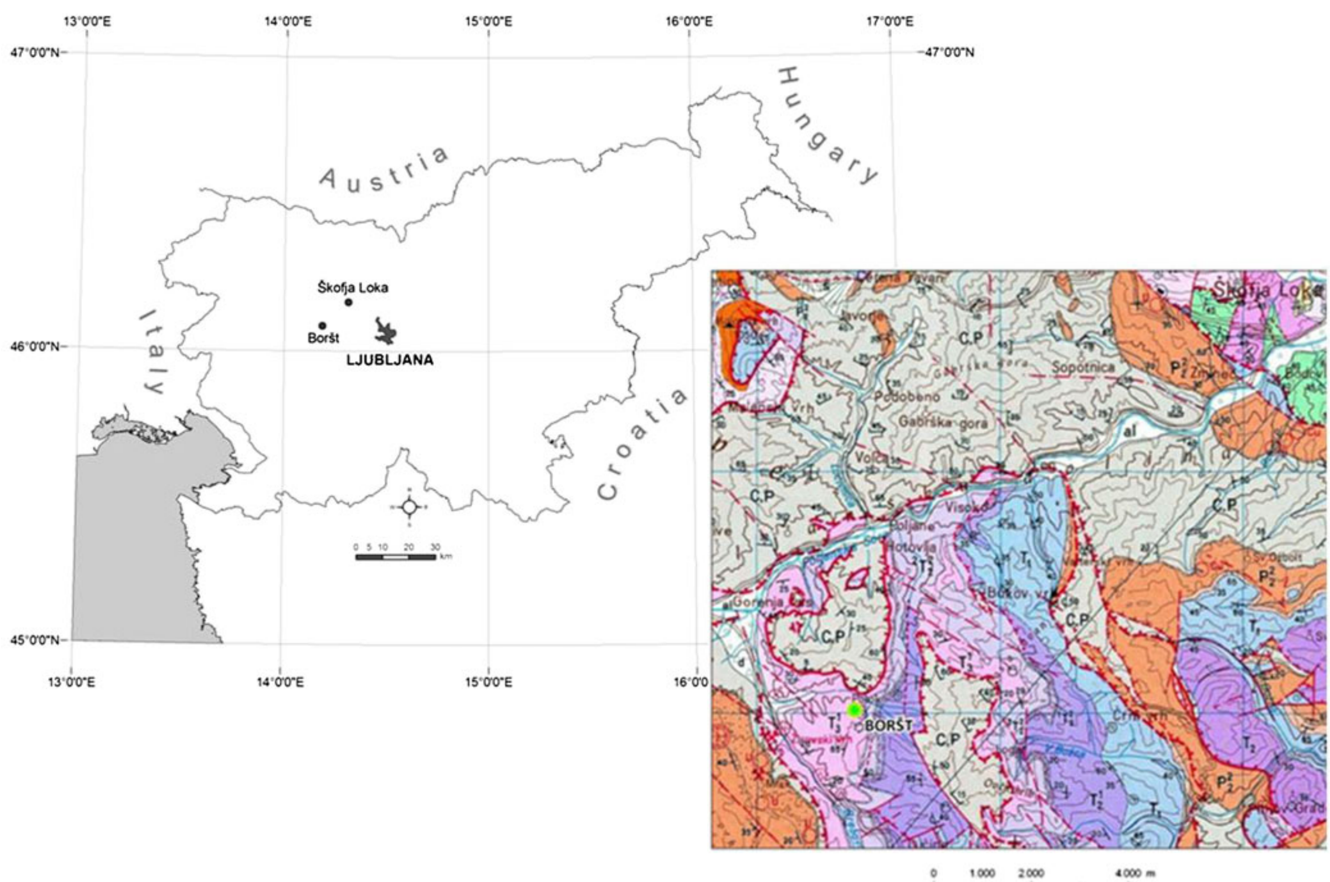

Fig. 1 Geological setting of Boršt and the Žirovski vrh areas (Grad and Ferjančič 1974) and their position in Slovenia (*C*, *P* Carboniferous and Permian mainly clastic rocks: claystone, siltstone, sandstone, fine graded conglomerate; limestone; P_2^2 gröden quartzite sandstone; T_1 limestone, dolomite, marl; T_2 dolomite; $^2T_2^2$ dolomite, limestone; T_3^1 sandstone, siltstone, tuff, limestone, dolomite)

material were excavated; out of these, 633,000 tonnes of uranium ore resulted in the production of 452 tonnes of uranium concentrate or yellow cake (U_3O_8—triuranium octoxide) (Florjančič 2000). The total reserves of the deposit were estimated at 16,000 tonnes of concentrate. Deposited at the Boršt site were 720,000 tonnes of low radioactive material, together with 70,000 tonnes of hydrometallurgical tailings. Some of the same material was also used for the consolidation of the access paths (Beguš 1994). The tailings consist of quartz, gypsum and sulphate salts. This material, with a particle size of under 0.6 mm, was relatively wet at deposition, with a moisture content of around 20 % which was later reduced to between 15 and 17 %.

The Boršt mill tailing deposit site was also a dumping site for the by-products of the uranium concentrate processing performed at the uranium mine, Žirovski vrh. Hence, it contains chemicals and radionuclides, which could have a long-term effect on the biosphere if they migrate into the air, the soil or the groundwater. The location of the Boršt area was chosen primarily on meteorological criteria rather than on the tectonic, hydrogeological and engineering geological conditions, as these do not entirely fit the uranium mine deposit standards (Beguš 1996). From the geomorphological aspect, the wider area of the Boršt mill tailing deposit site is very dynamic with relatively large slope inclinations (slopes range between 5° and 29°, average inclination is 12.3°). In addition, the area of Boršt is characterised by heavy rainfall and torrential streams. The average rainfall quantity for the wider area of the tailing location is 1,800 mm per year (ARSO 2012). The mill tailing deposit site was located above the temperature inversion limit (altitude, 535–570 m) and in an area with the presence of constant winds; these specifics facilitate the effective airing of the tailings with the purpose of eliminating radon emanations. The average emanation of radium-226 is 8,600 Bq/kg and the radon exhalation rate is 1–5 Bq/m^2s (Vrankar 2005).

The mill tailing deposit site was designed as a high, dry, homogenous earth dam. Necessary geotechnical studies, tests and analyses, in compliant with the standards, were performed on the tailings and on the excavated material dumped on the site. The earth dam body leans against the hinterland at the eastern, western and southern sides, which were without springs at the time of the dam's construction. Between 1987 and 1989, several boreholes were constructed for the purpose of monitoring the slope's stability, the groundwater table level and the potential groundwater pollution with radioactive nuclides (Likar 2000). Also, a geodetic net for surface movement monitoring was established. The first measurements before the landslide activation in 1990 showed the instability of the tailings of the Žirovski vrh mine disposed at Boršt.

Landslide

In November 1990, after heavy rain, a great landslide was initiated at the Boršt mill tailing deposit site. In the central Slovenia region, the months of October and November are usually the wettest months of the year and the total cumulative rainfall amount is approximately the same as the cumulative rainfall volume for the whole period from March to September, including the summer storms. Monthly rainfall distribution for the year 1990 and average monthly rainfall distribution for the period 1976–2005 are shown in Fig. 2.

In the initial period, the landslide velocity was up to 2 mm/day (Petkovšek 2004). The sliding mass included both the bedrock (the deposit site base) and the tailings, which together represented around 3 million cubic meters or more than 7 million tonnes of material. The mill deposit was constructed as a homogenous earth dam, but later analyses indicated that the interior of the dam was far from being a homogeneous mass (Petkovšek 2004). It also showed that in the 20 years of its existence (deposition), the tailing material had undergone mineral and compositional changes. These changes impacted the geomechanical characteristics of the tailings that governed the stability of the deposit. Transport roads made of tailings became the priority paths for surface water seepage. According to the extensive research performed between 1990 and 1994, the landslide extent, along with its surface, was defined (Fig. 3a). The sliding surface is located approximately 50 m below the mill tailing deposit surface, in the base rock (Fig. 3b).

The base of the Boršt disposal site consists mainly of the poorly permeable, tectonically fractured Carnian clastic rocks and Cordevolian dolomite in the hinterland (Fig. 4). When exposed to the atmospheric conditions, tectonically fractured Carnian clastic beds are extremely prone to weathering due to their mineralogical composition. Consequently, the groundwater easily penetrates through the tectonically fractured zones and potentially causes the high pore pressure levels that can lead to slope failure. Below the deposit site, groundwater from the Cordevolian dolomite infiltrates through the thrusting and tectonically damaged zones into the Carnian clastic beds. Thus, groundwater is the dominant pre-conditional factor for landslide instability in the Boršt mill tailing deposit site. Approximately, one third of the tailing material is wet or saturated by water. Above the groundwater table, some beds exist that include water under pressure (Petkovšek 2004). In the landslide-active period, from 1990 to 1995, the displacements of the mill tailing site ranged from 1 to 1.5 m, and the velocities ranged from 17 to 24 mm/month. Based on these results, the construction of the drainage tunnel was suggested with the purpose of stabilising the landslide. Also, drainage boreholes and drainage curtains in the tailing base were suggested. The drainage tunnel was built in 1995 and, consequentially, the displacement velocities reduced to a minimum (Fig. 5). In the last 2 years of the measurements (2011 and 2012), when precipitation amounts were way below the average, the landslide movements decreased to below 4 mm per year (Fig. 5). But on 20 May 2012, a strong earthquake with a magnitude of 6.1 occurred in Bologna, Italy, at a distance of 330 km W of the Boršt site. Despite a very dry period, that earthquake caused a significant displacement of the landslide mass in the range of 9 mm, as shown by the extensometers inside the drainage tunnel within the landslide (Fig. 5) (Gantar 2012). In recent times, displacements of the landslide mass have been very small, but from time to time, mostly depending on rainfall intensity, the shifts can be notable.

Remediation works at the Boršt mill tailing deposit site ended in 2010 and the transition (stabilisation) period of 5 years, when the stable conditions regarding the potential environmental impacts have to be achieved in order for the final declaration of the effectiveness of the remedial measures to be issued, is ongoing.

Methods

The persistent scatterer interferometry

PSI is an interferometric technique based on the phase comparison of synthetic aperture radar (SAR) images, gathered at different times with slightly different looking angles (Gabriel et al. 1989;

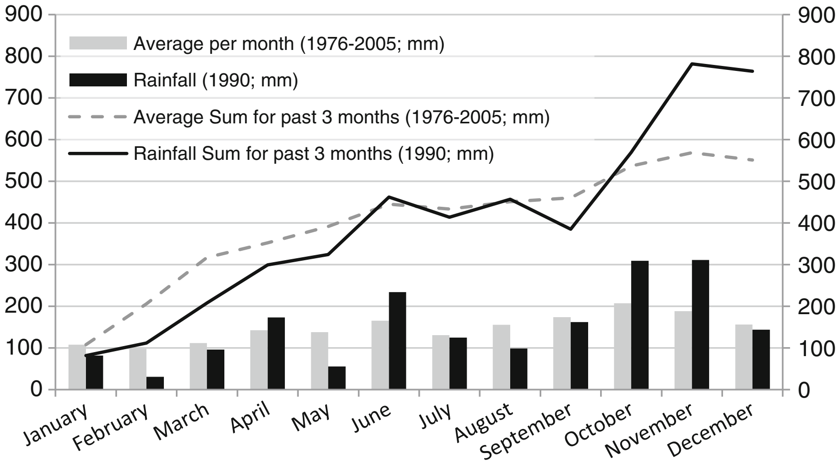

Fig. 2 Monthly rainfall distribution for the year 1990 (*dark bars*) and average monthly rainfall distribution for the period 1976–2005 (*light grey bars*) (ARSO 2013). *Dotted line* represents the average of the sum precipitation for the three preceeding months for the period 1976–2006 and the *dark line* represents the sum precipitation for the three preceeding months for the year 1990 when the landslide was triggered. The *bar scale* is on the left and the *line scale* is on the right of the chart. All values are in millimetre

Bamler and Hartl 1998; Rosen et al. 2000). The PSI technique represents an upgraded version of the differential radar interferometry technique in which the main limitations are linked to the loss of coherence with time to the influence of atmospheric artefacts and the presence of uncompensated topography. The PSI technique overcomes some of these drawbacks and is capable of detecting isolated coherent pixels and tackling the problem of atmospheric delay errors at the expense of a large number of required images (>20) and a sparse, pixel-by-pixel based evaluation (Ferretti et al. 2000, 2001). Point targets, referred to as persistent scatterer (PSs), are not affected by temporal decorrelation and are recognised by means of a statistical analysis of their amplitude in all available SAR images. The contribution of topography, deformation and atmosphere can be estimated by carefully exploiting their different behaviours in time and space. An abundant archive of SAR satellite imagery allows analyses of the PS displacements since 1992, which is scarcely possible with traditional methods such as GPS/GNSS surveys. Due to the possibility of measuring deformations with millimetre accuracy, the PSI method is suitable for detecting and investigating slow slope

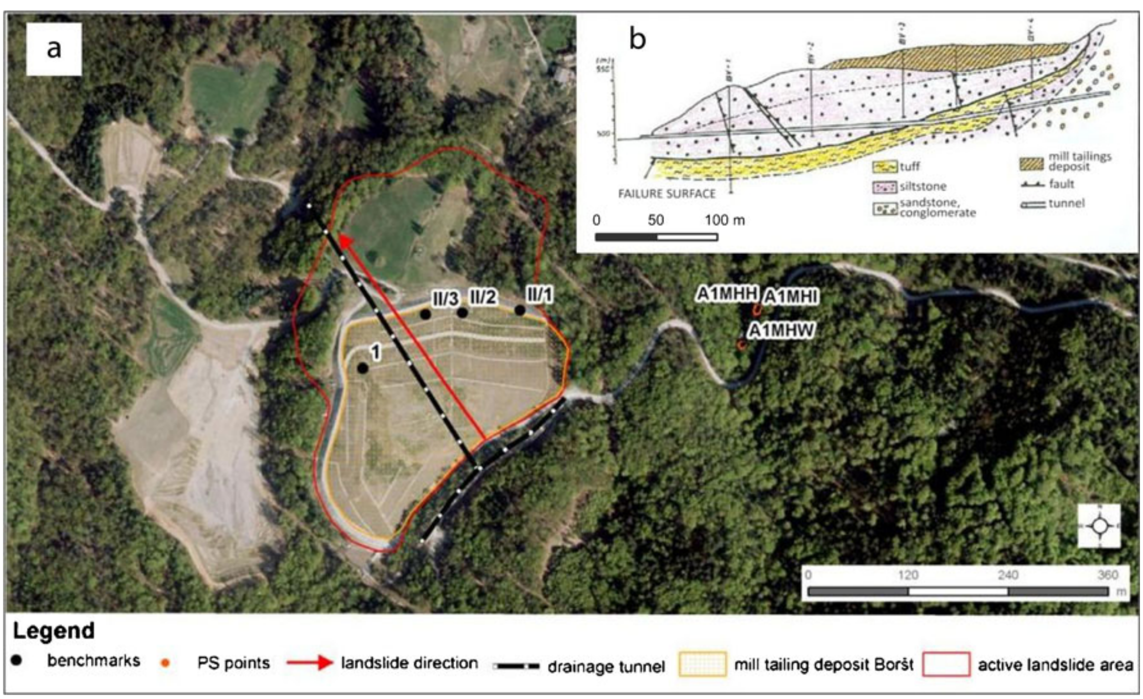

Fig. 3 **a** Boršt mill tailing deposit site after remediation works in 2007. *Black dots* represent the position of the benchmarks; *orange dots* represent persistent scatterer (PS) points; *red arrow* represents landslide direction; *red polygon* indicates active landslide area and *black–white line* shows the position of the drainage tunnel. **b** The cross section profile through Boršt along the drainage tunnel (adapted from Likar 2000)

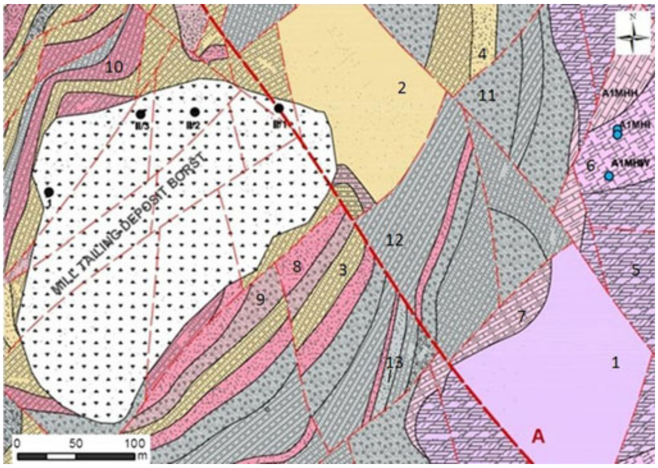

Fig. 4 Geological settings of the wider area of Boršt (Čar 2010) and the locations of the benchmarks, marked by *black dots*, and PS points, marked by *blue dots*. Numbers at the lithological units characterised: *1* light grey dolomite (${}^{4}T^{3}_{1}$); *2* yellow/grey siltstone, sandstone (${}^{3}T^{3}_{1}$); *3* yellow/grey siltstone, sandstone (${}^{3}T^{3}_{1}$); *4* yellow/grey sandstone (${}^{3}T^{3}_{1}$); *5* light grey dolomite (${}^{4}T^{3}_{1}$); *6* dark grey limestone (${}^{2}T^{3}_{1}$); *7* dark grey limestone (${}^{2}T^{3}_{1}$); *8* red sandstone (${}^{3}T^{3}_{1}$); *9* red/violet sandstone, conglomerate (${}^{3}T^{3}_{1}$); *10* red siltstone, sandstone (${}^{3}T^{3}_{1}$); *11* grey sandstone, conglomerate (${}^{3}T^{3}_{1}$); *12* green/grey siltstone, sandstone (${}^{3}T^{3}_{1}$); *13* grey sandstone (${}^{3}T^{3}_{1}$). A *bold red* fault marked by '*A*' separates the II/1 benchmark from benchmarks II/2, II/3 and 1

deformation, where the velocities of ground motion do not exceed half of the radar wavelength (2.83 cm for the European remote sensing satellite (ERS) satellite) between the two consecutive data acquisitions (35 days for the ERS satellite). If this happens, movements cannot be detected and loss of coherence can occur (Canuti et al. 2004; Metternicht et al. 2005). In addition, the microwave radar is only sensitive to displacement changes in the radar line of sight (LOS; azimuth 193.14°; declination from the vertical axis 23.26°) direction in relation to the stable reference point, which is assumed to be motionless. To define the real movement of a target (PS) in the three-dimensional system, one can combine the LOS information from the ascending and the descending orbits (Bürgmann et al. 2000). However, not every scanned area has the ability to enable data acquisition from both campaigns due to limiting factors at the time of scanning, such as geometric distortion, the atmospheric phase screen (Zebker and Villasenor 1992) and terrain topology (shadowing effect of steep slopes, unfavourable slope orientation, etc.). A more detailed review of the PSI technique can be found in Massonnet et al. (1996), Ferretti et al. (2000, 2001), Colesanti et al. (2003) and Colesanti and Wasowski (2006).

When PSI data from only one orbit are available, the displacements parallel to the slope gradient can only be calculated using the projection of unitary vector (sensitivity versor; u) that is relative to the reference point, a geologically stable point close to the nadir of the whole radar image (also scene) (Massonnet et al. 1996; Colesanti et al. 2003). The displacement (d_{LOS}) in the LOS is a scalar product (Eq. 1) of the sensitivity versor, a vector defining the look direction (LOS) of the satellite (satellite look direction vector u [0.384, −0.089, 0.918]) and the actual displacement of the observed PS (d) (Colesanti and Wasowski 2006). This approach is especially useful when the main displacements are suspected to be occurring in the direction perpendicular or sub-perpendicular to the LOS, t.i. in the north–south direction, which is anticipated to be the main displacement direction in the case of the Boršt mill tailing site. In the case of translational landslides, the main component of the displacement vector is suspected to occur along the slope gradient (along which the sliding mass would most probably move) and is defined by the unit vector of the slope gradient direction d^{T} $[x, y, z]$ calculated from the average slope angle downhill within a reasonable distance (dependent upon the length of the slope) from the PS. The coordinate system used for this scalar product calculation is a positive-up, right-handed coordinate system.

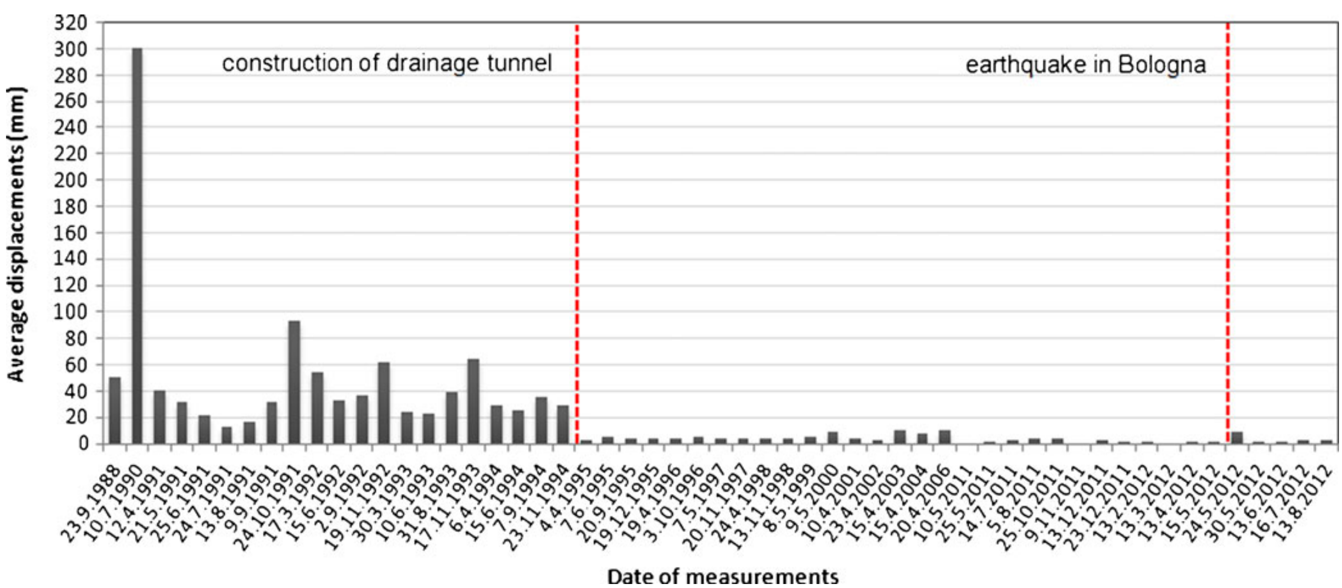

Fig. 5 Overview of the average displacement rates as measured at the benchmarks and extensometers located within the mill tailing deposit between 1988 and 2012. In the period between 2007 and 2010, the construction works were implemented in the mill tailing deposit and the rates were not accurate

The displacement (d_{LOS}) in the LOS is thus defined with the following equation (Colesanti and Wasowski 2006):

$$d_{LOS} = d \times u = [d_{East}, d_{North}, d_{Zenith}] \times [u_{East}, u_{North}, u_{Zenith}]. \quad (1)$$

Assuming S is the amplification of the range-change rate when projected into the slope gradient (downslope direction) vector and d^T is the transpose of d, the following equation can be written (Hilley et al. 2004):

$$S = 1/(d^T \times u). \quad (2)$$

S simply represents the actual to detected displacement ratio. Knowing the d_{LOS} values, actual d values are easily derived (Eq. 3) and comparison of radar interferometric measurements to the ground survey (in situ) measurements can be performed directly.

$$d = d_{LOS} \times S \quad (3)$$

In the wider study area, 67 ERS scenes were acquired between June 1992 and December 2000 along the descending orbits (consequently also meaning 67 measurements were acquired) and were used for the interferometric analyses of the Škofja Loka and Cerkljansko areas. A total of 2,787 PSs were identified, mainly corresponding to outcrops and man-made structures, such as building, poles and antennas. The geocoding accuracy of the PS locations was approximately ±15 m in the east–west and ±4 m in the north–south directions, while the estimated accuracy of the elevation values was usually better than 2 m. The LOS direction displacement rates varied from +7.26 to −18.75 mm/year, relative to the reference point located in the town Železniki (46°13′29.13″ N, 14°10′31.77″ E). This means that for each PS, every measurement of displacement value in the LOS is expressed in relation to the 'stable' (presumed motionless) reference point. By combining results from several measurements, time series of the displacements were acquired for individual PSs.

Unfortunately, no PSs were detected on the mill tailing deposit site, but three PSs (A1MHI, A1MHH and A1MHW) lie approximately 250 m away on the same slope. Field surveys confirmed the interpretation from the orto-photo that two PSs (A1MHI and A1MHH) coincide with the outcrop, while PS A1MHW was determined by the rubble deposit and consequently, the values measured at this location are most probably subject to high uncertainty (due to the additional tumbling process of the surface rubble) and may not represent the real natural ground movements. All three PSs are located east of the mill tailing deposit site (Fig. 3a). The results of the detailed geological mapping of the area (Čar 2010) indicate that aside from the mill tailing site, the whole slope might also be subject to sliding, approximately in the direction of north-west (Figs. 3a and 4). For simplification of the comparison between PSI and in situ data, we assumed that the part of the slope where the PSs are located is also moving as one mass towards the valley bottom. Hence, we put the mill tailing site and the PS locations on the same hypothetical geologically structural homogeneous unit. From comparison of the actual displacement vectors of the benchmarks and from the morphological properties, the assumed displacement PS vectors, as shown in the Table 1, confirm this thesis. Values of azimuth and the sliding angle of both types of measurement points clearly show almost identical sliding directions (azimuth of displacement column) and angles (downslope displacement angle column). In the case of azimuth values, the difference ranges from 0.5° to 11.4°, while in the case of downslope angles, the difference ranges from 0.3° to 6.8°. The largest difference in the downslope angle could be explained by very local conditions that govern the sliding process. Taking into account the relatively small differences in movement directions of the two groups of measurement points (especially the azimuth values), the comparison between the in situ and remote-sensing measurements was justifiable and all comparisons were made on the actual vectors and not their projections to any axis.

Table 1 Properties of displacement vectors for benchmarks (II/1, II/2, II3 and 1) and for PS (A1MHI, A1MHH and A1MHW)

Measurement location	Downslope displacement angle	Azimuth of displacement
1	−19.6	347.0
II/1	−17.9	342.3
II/2	−25.3	345.6
II/3	−20.5	345.4
A1MHH	−20.10	349.3
A1MHI	−20.10	349.3
A1MHW	−18.47	353.1

Conventional in situ studies

Conventional in situ studies of geotechnical surveys around the mill tailing deposit site consisted of boreholes, a drainage tunnel, trench pits and displacement measurements at benchmarks. Measurements of the stability of the Boršt mill tailing deposit site began in August 1988 and were continued until 2012, using different techniques, such as extensometers, inclinometers and benchmarks (using triangulation and trilateration methods). Precise displacement measurements, using the latter, were performed at four locations (benchmarks II/1, II/2, II3 and 1) (Fig. 3a) from September 1988 until April 2006, and altogether in this the period, 38 measurements were acquired. As no vertical component was available from the benchmark measurements, we assume that the displacements were sub-horizontal.

After the extensive renovation of the mill tailing deposit site in 2007 and 2008, these benchmarks were completely destroyed. Thus, from 2009 onwards, precise geodetic measurements have

Table 2 Parameters of the slope gradient vectors (d^T) that run through each PS, the sensitivity versor parameters (u) and actual to detected displacement ratios (S)

PS	d^T_{Eeast}	d^T_{North}	d^T_{Zenith}	S
A1MHH	−0.185	0.983	−0.344	2.104
A1MHI	−0.185	0.983	−0.344	2.104
A1MHW	−0.111	0.9940	−0.317	2.364
	u_{East}	u_{North}	u_{Zenith}	S
Sensitivity versor (u)	0.38462	−0.08978	0.9187	1

been performed using the geodetic networks ('Network' and 'Network Plaz') and by stationary GNSS stations. Figure 3a shows the landslide at the Boršt mill tailing deposit site with locations of in situ benchmarks and PSs in the vicinity of the landslide. Benchmarks (II/1, II/2, II3, 1) are indicated with black circles and the PSs (A1MHI, A1MHH, A1MHW) are marked by orange circles. All are used in the present study, and only measurements at benchmarks are regarded hereafter as the in situ data.

Measurements comparison

For the comparison of the PSs and the in situ methods, temporal series correlation tests and trends of displacements were used. All correlation tests were performed using the Pearson product–moment correlation coefficient (*r*) formula and values represent linear correlation coefficients. For deriving displacement trends, a linear regression model with a least square method was used for the three types of data—for PSI for the whole comparison period (1992–2001), for the in situ data for the measurements performed

Table 3 In situ detected displacements for the period June 1992 to April 2001 (cumulative values in millimetre relative to the status on 15 June 1992) and PS displacements (*d*) along the slope gradient vector (cumulative values in millimetre from the start of the data acquisition, 11 June 1992). Date difference column represents the difference between the two acquisitions in days (n.a.—acquisition was not possible due to the satellite failure)

Date of in situ measurements	II/1 (mm)	II/2 (mm)	II/3 (mm)	1 (mm)	Date of PSI acquisition	A1MHI′ (mm)	A1MHH′ (mm)	A1MHW′ (mm)	Date difference (in situ—PSI)
15 June 1992	0	0	0	0	11 June 1992	0	0	0	4
2 September 1992	−11.3	−41.4	−41.4	−55	24 September 1992	−23.9	−29.6	−28.8	−22
19 November 1992	−29.7	−111.4	−116.5	−138.6	03 December 1992	−25.6	−27.9	−26.3	−14
30March 1993	−37.2	−139.7	−145.6	−172.4	22 April 1993	−28.9	−33.6	−49.6	−23
10 June 1993	−48.2	−162.3	−171	−203.9	01 July 1993	−44.9	−47.4	−60.9	−21
31 August 1993	−67	−201.4	−213.3	−258.5	09 September 1993	−30.9	−48.2	−67.5	−9
17 November 1993	−82.9	−275.8	−292.2	−349.6	18 November 1993	−51.9	−57.4	−86.6	−1
6 April 1994	−91.4	−307.9	−325.8	−391.2	n.a.	n.a.	n.a.	n.a.	–
15 June 1994	−100.2	−335.2	−356.5	−426.6	n.a.	n.a.	n.a.	n.a.	–
7 September 1994	−118.6	−372.7	−394.6	−473.6	n.a.	n.a.	n.a.	n.a.	–
23 November 1994	−134.5	−408.5	−426.5	−505.2	n.a.	n.a.	n.a.	n.a.	–
4 April 1995	−136.7	−410.9	−429.6	−507.7	20 May 1995	−59.4	−74.7	−125.8	−46
7 June 1995	−147.9	−415.5	−434.1	−509.2	24 June 1995	−38.7	−82.5	−134.3	−17
20 September 1995	−151.6	−419.5	−439.4	−512.7	03 September 1995	−63.7	−78.9	−148.6	17
19 December 1995	−157	−421.5	−443.2	−515.4	08 October 1995	−61.9	−79.3	−156.8	72
19 April 1996	−161.8	−424.7	−447.3	−517	04 May 1996	−65.8	−67.5	−177.2	−15
3 October 1996	−168.8	−430.3	−454.5	−519.8	22 September 1996	−81.1	−92.2	−214.8	11
7 May 1997	−170.2	−435.1	−457.4	−523.8	25 May 1997	−85.9	−96.6	−217.6	−18
20 November 1997	−176.9	−438.1	−460.8	−527.5	16 November 1997	−102.8	−111.4	−252.6	4
24 April 1998	−183.7	−440.3	−463.3	−530.7	10 May 1998	−105.1	−114.5	−247.1	−16
13 November 1998	−187.4	−446.9	−466.8	−532.5	01 November 1998	−116.0	−127.6	−299.4	12
8 May 1999	−196.1	−449.8	−470.4	−535.5	30 May 1999	−118.6	−127.9	−310.5	−22
9 May 2000	−210.7	−460.1	−477.4	−539.9	14 May 2000	−127.6	−155.6	−354.3	−5
10 April 2001	−218.4	−461.8	−481.4	−543.7	10 December 2000	−145.7	−166.7	−415.0	121

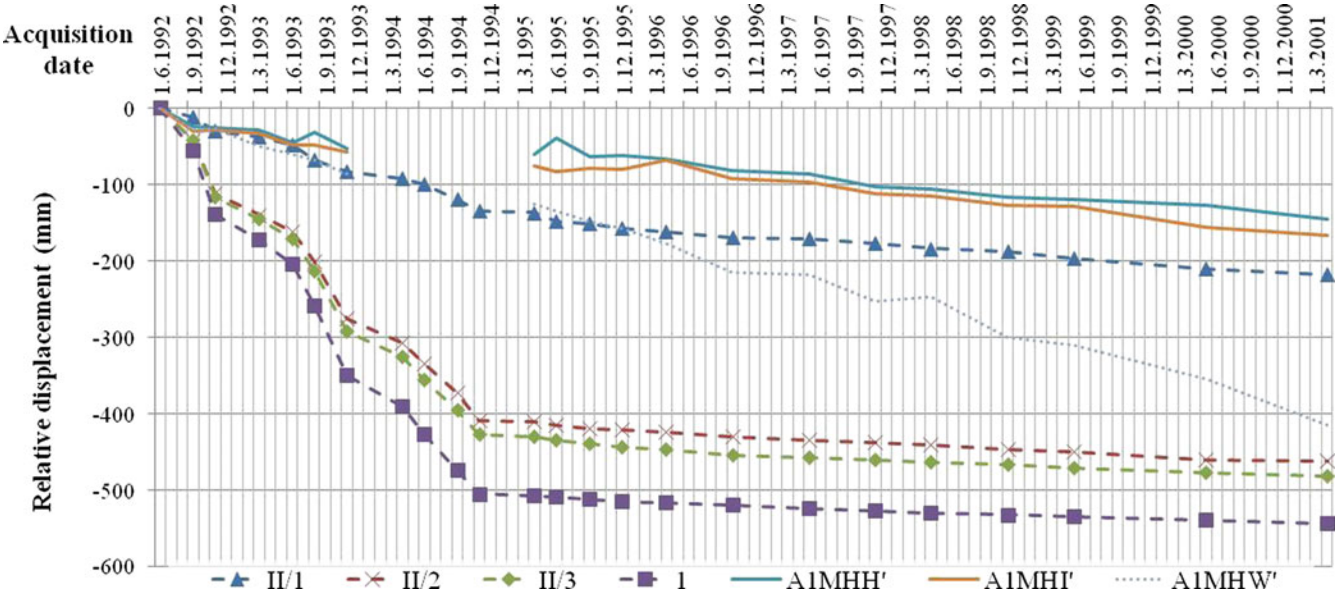

Fig. 6 Displacements of PS points (A1MHI′, A1MHH′ and A1MHW′) and in situ conventional surveys (II/1, II/2, II/3, 1) in the period from 1992 to 2001. All values are relative to the first acquisition value/status in the period of displacement comparison

prior to the drainage tunnel construction (pre-mitigation period; 1992–11/1994) and for the measurements performed after the drainage tunnel construction (post-mitigation period 04/1995–2001). The observation period for the in situ data was split due to notable change in the displacement trend after construction of the drainage tunnel.

Only deformations detected by PSI that temporarily overlap with the data from benchmark measurements were compared. Hence, comparison of the two data sets was performed only for the period from June 1992 to April 2001, although in situ measurements from the mill tailing deposit site are available for the period 1988 to 2006. Cumulative displacement values at four locations (II/1, II/2, II/3, 1) on the mill tailing deposit site, where also the largest displacement values were detected, were compared with the displacements (projected on the slope gradient vector) detected at three PS locations (Fig. 3a).

Results and discussion

In order to examine the spatial (and consequently the temporal) relationship between various datasets, a GIS layer was created in ArcMap 9.3, combining the PS point data and the data from the conventional in situ measurements. Table 2 shows the *S* value for each PS, calculated from the scalar product of the slope gradient vector (d^T) that runs through that specific PS and the sensitivity versor (u). Based on Eq. 3, *S* values were used to derive (near) actual displacement values (d) at the PSs ('denoted with') along the suspected direction of sliding. These are represented in Table 3.

As the dates of the in situ measurements and the PSI acquisitions were not synchronised, for comparison purposes, we chose the closest dates from both acquisition approaches. Table 3 represents the cumulative displacement values (in millimetre) for the conventional in situ investigations and for the PSI remote-sensing monitoring along the slope gradient, both for the period June 1992 to April 2001. The last column shows the difference in the acquisition dates between the in situ and PSI measurements. The average difference was 26 days, with a maximum of 121 days and a minimum of 1 day.

Of all 2,787 PS locations included in the PSI campaign data, only three PSs were located near the active landslide or mill tailing deposit site (Fig. 3a). The PS displacements along the slope gradient vector range from 1.7 to 4.9 cm/year, and this could correspond to the slope-creep process, which Vulliet (1999) defines as all slope mass movements with velocities ranging from 1 to 10 cm/year. Figure 6 shows displacements of the PSs (A1MHI′, A1MHH′ and

Table 4 Correlation coefficients (square values of Pearson correlation coefficients (R^2)) between the in situ (II/1, II/2, II/3 and 1) and PSI (A1MHH′, A1MHI′ and A1MHW′) temporal series of displacements

		A1MHH—real	A1MHI—real	A1MHW—real
Pre	II/1	0.856	0.918	0.964
1992–November 1994	II/2	0.885	0.921	0.964
	II/3	0.882	0.919	0.963
	1	0.883	0.924	0.966
Post	II/1	0.958	0.954	0.987
April 1995–2001	II/2	0.971	0.957	0.986
	II/3	0.968	0.925	0.973
	1	0.981	0.950	0.982

Table 5 Slope of the linear regression functions, square values of Pearson correlation coefficients (R^2) for the linear regression functions, average velocities of each location (v) in millimetre per year, and for the in situ measurements, ratio of average velocities prior to and after the remediation works (pre to post v ratio)

Benchmarks	II/1	II/2	II/3	1
Pre (1992–November 1994)	−0.1445	−0.4464	−0.4722	−0.5619
R^2	0.9856	0.9864	0.9863	0.9867
v (mm/year)	−55.1	−167.34	−174.72	−206.96
Post (April 1995–2001)	−0.0340	−0.0230	−0.0225	−0.0164
R^2	0.9802	0.9827	0.9529	0.9811
v (mm/year)	−13.57	−8.45	−8.6	−5.98
Pre to post v ratio	4.06	19.8	20.31	34.62
Persistent scatterers	A1MHH′	A1MHI′	A1MHW′	
1992–2001	−0.040	−0.0442	−0.1202	
R^2	0.9547	0.9631	0.9935	
v (mm/year)	17.14	19.6	48.8	

A1MHW′) relative to the reference point and in situ displacements, both in millimetre and for the period from 1992 to 2001. Table 4 shows the correlation coefficient values between the in situ and PSI temporal series of displacements. As all coefficients are very high, indicating a good relation between the two types of measurement and confirming that, at least to a certain level, all locations are subject to some common movement effect (i.e. sliding of the whole hill, or expansion and compaction of the soil, or even mass movements due to changes in the atmospheric/air pressure (Schulz et al. 2009)), the real information lies in the enhancement of the correlation after the remediation measures at the site that were undertaken at the beginning of 1995. Before the remediation, the minimum of the correlation coefficients was 0.86, while the minimum of the correlation coefficients after the remediation rose to 0.925. Higher correlation values in the post-remediation period indicate that the fluctuations in the displacement values at the landslide were very similar to those at the PSs that could be treated as a background to the site, and that the residual displacements are related to the broader, maybe even more regional, dynamic processes that cannot be easily evaluated.

When comparing the PSI data and in situ conventional surveys in the period from 1992 to 2001, it can be seen (Fig. 6) that the movement trends of the PS points are relatively constant, while movements of the benchmarks notably differ after the remediation works in 1995 (construction of the drainage tunnel). The comparison of the statistical parameters (Table 5) indicates that pre-remediation velocities of benchmark II/1 are similar to the velocities of PS A1MHW, while the pre-remediation velocities of benchmarks II/2, II/3 and 1 are up to four times higher than the velocity of PS A1MHW. As the reliability of the latter is highly questionable due to its position on the rubble deposit, the comparison is also very unreliable. What can be concluded is that, in the pre-remediation phase, benchmark II/1 moved at the speed of freely tumbling rubble down the slope.

The similarity of the average velocities between the two more reliable PSs and the post-remediation velocity of benchmark II/1, their geographical relation (they are the closest) and the presence of the fault that dissects the landfill and landslide, and separates the II/1 benchmark from the others (Fig. 4), implies that benchmark II/1 and PSs A1MHH and A1MHI are located on a slightly different structural sub-unit than the three other benchmarks. The velocity differences between benchmark II/1 and the other three benchmarks in the post-remediation period also suggests that the groundwater drainage effect of the drainage tunnel has a much higher effect on benchmarks II/2, II/3 and 1 than it has on II/1. This fact is far from surprising as the tunnel lies beneath and close to (less than 50 m) the first three benchmarks and more than 100 m from II/1 (Fig. 3a). Nevertheless, some effect on slowing the landslide-moving mass was also achieved with the drainage tunnel even at more distal landslide parts (i.e. II/1), where the velocities of the mass movement slowed down by a factor of 4 to 13.6 mm/year. The highest reductions in velocities of the sliding mass were detected closer to the drainage tunnel, where velocities of the landslide slowed down by a factor range between 19.8 and 34.6 to velocities between 8.45 and 5.98 mm/year, respectively. Assuming that the downslope velocities of the PSs are the background movement of the whole area or the hill, the remediation works effectively eliminated the cause of the landslide movement (the groundwater effect) at benchmark II/1 in the post-remediation period when the velocity of the latter very much resembles the velocities of the first two. We can anticipate that the same effect was achieved for the rest of the landslide body, where benchmarks II/2, II/3 and 1 are located, as the post-remediation velocities there are even lower than at II/1 or for PSs.

Conclusions

Uranium mine and mill tailings are hazardous waste due to the radioactive and toxic elements that remain from the ore deposits. Catastrophic or continuous release of contaminants can have a substantial impact on the environment. Surface remedial action mainly consists of stabilising the tailings on site; active remediation of contaminated groundwater is required for complete remediation of certain mill tailing sites. Slovenia was one of several EU countries where the excavation of uranium was undertaken in the past. At the Boršt mill tailing site in central Slovenia, a relatively large and fast landslide occurred at the November 1990. In this paper, we compared the results of the mass displacement measurements, acquired by two different techniques, an in situ technique and a satellite remote-sensing radar interferometric technique.

We have compared the pre- and post- remediation velocities at the benchmarks located on the landslide, with the PSs located near the landslide, but far away enough to be regarded as a background.

The results showed that the remediation works in the form of a drainage tunnel were very effective, as post-remediation velocities at the part of the landslide closer to the PSs resembled the velocities of the PSs, while the velocities of the landslide mass above the drainage tunnel were slowed down, even to below the background velocities.

The high correlation values between the movements of the benchmarks and the PSs also confirm that the remediation works were effective as the fluctuations in the displacement values of the landslide were very similar to those at the PSs (treated as a background to the site). These correlation values also imply that the residual displacements are related to the dynamic processes that cannot be easily evaluated.

The best and ideal measurement results for monitoring and comparison would, however, be achieved if both types of measurement points, benchmarks and PSs, were to be organised in a survey network with units located on the landslide and in the background and if the measurements were to be acquired on the same dates. Such an approach would benefit the improving of the levelling or the GPS surveying networks by relocating or adding new measurement points and borehole inclinometers based on the PS displacement results (Colesanti et al. 2003). Likewise, through the identification of ground instability areas with conventional in situ methods, new locations for artificial stable reflectors or active radar transponders can be located to monitor unstable slopes with millimetric precision at relatively low cost. Additionally, these findings could and should encourage further continuous monitoring of the research area with artificial PSs to provide new information on the displacement rates that can be the basis for further reconstruction work.

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