Evidence of rock slope breathing using ground-based InSAR

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Article history:
Received 16 May 2015
Received in revised form 30 June 2016
Accepted 4 July 2016
Available online xxxx

Keywords:
Rock slope
Stability
Rockslide
Ground-based InSAR
SAR interferometry
Groundwater effect

A B S T R A C T

Ground-Based Interferometric Synthetic Aperture Radar (GB-InSAR) campaigns were performed in summer 2011 and 2012 in the Romsdalen valley (Møre & Romsdal county, western Norway) in order to assess displacements on Mannen/Børa rock slope. Located 1 km northwest, a second GB-InSAR system continuously monitors the large Mannen rockslide. The availability of two GB-InSAR positions creates a wide coverage of the rock slope, including a slight dataset overlap valuable for validation. A phenomenon of rock slope breathing is detected in a remote and hard-to-access area in mid-slope. Millimetric upward displacements are recorded in August 2011. Analysis of 2012 GB-InSAR campaign, combined with the large dataset from the continuous station, shows that the slope is affected by inflation/deflation phenomenon between 5 and 10 mm along the line-of-sight. The pattern is not homogenous in time and inversions of movement have a seasonal recurrence. These seasonal changes are confirmed by satellite InSAR observations and can possibly be caused by hydrogeological variations. In addition, combination of GB-InSAR results, in situ measurements and satellite InSAR analyses contribute to a better overview of movement distribution over the whole area.

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1. Introduction

The detection, characterization and assessment of unstable slopes require a multidisciplinary approach, including mapping, field and laboratory measurements, modelling, etc. (e.g. Solheim et al., 2005; Jaboyedoff et al., 2005). The characterization of movement rate, distribution and evolution is a fundamental part in order to understand the behaviour of unstable slopes and forecast potential collapse events (e.g. Costa and Agliardi, 2003; Petley et al., 2005; Blikra, 2008; Federico et al., 2012; Blikra and Kristensen, 2013; Froese and Moreno, 2014). In Norway, a classification system has been developed by the Norwegian Geological Survey (NGU) and is currently used to systematically evaluate the hazard and risk of unstable slopes. Among the nine main criteria used to score the hazard, two are related to the slide velocity and changes in displacement rates (Hermanns et al., 2012, 2013). Various tools and instrumentation are used to measure these parameters. For the last decades, the development of remote sensing has had a major impact in this field (e.g. Mantovani et al., 1996; Metternicht et al., 2005; Michoud et al., 2010; Derron et al., 2011; Jaboyedoff et al., 2012). In Norway, active optical and microwave remote sensing techniques are used for the detection, mapping and monitoring of unstable slopes (e.g. Lauknes et al., 2010; Dehls et al., 2014; Oppikofer, 2016). They have proved being particularly valuable for operational reasons, due to its large coverage capability, high resolution and accuracy, and the possibility to document areas difficult to access.

The contribution of active microwave remote sensing for detection, mapping and monitoring of ground displacements using Synthetic Aperture Radar Interferometry (InSAR) has got an international scientific recognition at the beginning of the nineties (Gabriel et al., 1989; Massonnet et al., 1993; Zebker et al., 1994). Firstly developed for space borne platforms, InSAR devices were then developed for ground-based acquisitions (GB-InSAR). At the end of the nineties, a prototype of outdoor portable SAR system LISA (Linear Synthetic Aperture radar) was available (Tarchi et al., 1999; Luzi, 2010). Since then, the use for mapping and monitoring of slope instabilities has quickly increased and numerous case studies have been reported (e.g. Tarchi et al., 2003; Noferini et al., 2007; Herrera et al., 2009; Gischig et al., 2009; Barla et al., 2010; Casagli et al., 2010; Del Ventisette et al., 2011; Bozzano et al., 2011; Herrera et al., 2011; Intieri et al., 2012;
Mannen/Børa rock slope

2.2. Mannen rockslide

The main unstable area of Mannen rockslide is about 500 m wide and 600 m long. It is located between 1290 and 600 m a.s.l.: between 1230 and 540 m above the valley bottom. It is delimited at the top by a steep backscarp of about 25 m (Fig. 2, top).

The instability is known from the end of the nineties. Since this time, various studies have been carried out in order to know its geometry and its activity. These include structural analyses (Henderson and Saintot, 2007; Dahle et al., 2008, 2010; Saintot et al., 2011a, 2012), Terrestrial Laser Scanning (TLS) (Longchamp et al., 2010; Saintot et al., 2011a), boreholes (Saintot et al., 2011a; Elvebakk, 2012), 2D resistivity survey (Dalsegg and Rønning, 2012), run-out modelling and risk assessment (Dahle et al., 2011).

From field campaigns, it appears that the foliation has an average dip direction to S-SE and a penetrative steep dip angle. However, the area is located in a high-grade metamorphic unit intensively folded and is thus affected by significant variations of the foliation (Saintot et al., 2011a, 2012). The area is highly fractured and includes several subvertical sets, as well as penetrative discontinuities that wedge-shape the upper part of the instability (Henderson and Saintot, 2007; Dahle et al., 2010; Saintot et al., 2011a, 2012). In addition to field measurements, structural analysis based on Terrestrial Laser Scanning (TLS, point spacing: ≤7 cm) and Aerial Laser Scanning (ALS, DEM resolution: 1 m) datasets has been performed (Longchamp et al., 2010) using the Coltop3D software (Terranum Ltd.) designed to identify sets of discontinuities from point clouds (Jaboyedoff et al., 2007). The results are shown as stereonets in Fig. 3. Comparing them to the field data, J3 can be identified as the foliation plane, J1/J1′-2′ as main sets involved in the wedging and sliding processes and J5/J6 as two major subvertical sets back-shaping the instability (Rouyet, 2013).

Based on these investigations, possibly unstable volumes and corresponding collapse scenarios were outlined (Dahle et al., 2010). The instability A has a failure surface estimated at 40–80 m deep and a volume of 2–4 Mm³, while the second instability (B) has an estimated 70–110 m deep failure surface and a volume of 15–25 Mm³. A third instability (C) includes a larger volume further southeast, estimated to 80–100 Mm³ (Saintot et al., 2011a, Fig. 2, bottom).

Mannen is considered as a high risk rockslide (Blikra et al., 2010), combining high probability of occurrence and high potential casualties and damages (Dahle et al., 2011). It threatens houses, roads and a railway track, either directly in the potential run out zone, or indirectly, in case of river damming and outburst (Hermanns et al., 2013b). Thus, since 2009, a continuous real-time monitoring network including...
Fig. 2. Edges of Mannen and Børa instabilities according to Braathen et al. (2004), Dahle et al. (2010), Saintot et al. (2011a) and Dahle et al. (2011). Top: Pictures of Mannen scarp corresponding to the upper edge of instability A (Rouyet, 11.08.2011) and Børa plateau with edges of small (full lines) and large (dashed line) instabilities and networks of cracks (dotted lines) (Rouyet, 20.08.2012). Bottom: Map of Mannen and Børa instabilities. Location in Fig. 1. Background: hillshade from 1 m DEM.

Please cite this article as: Rouyet, L., et al., Evidence of rock slope breathing using ground-based InSAR, Geomorphology (2016), http://dx.doi.org/10.1016/j.geomorph.2016.07.005
differential GPS (DGPS), laser-reflectors, extensometers, tiltmeters, a meteorological station and a GB-InSAR system (locations in Fig. 4) has progressively been implemented (Blikra et al., 2010; Kristensen and Blikra, 2013). The Norwegian Water Resources and Energy Directorate (NVE) is in charge of the monitoring. In autumn 2014, significant acceleration in an area with a volume estimated to 120,000–180,000 m$^3$ was recorded in the upper western part of instability B, called Veslemannen. Inhabitants were evacuated and a high alarm level was maintained several weeks before winter stabilization (Skrede et al., 2015).

### 2.3. Børa plateau

Located at the southeastern edge of Mannen rockslide, Børa is an approximately 3 km long and 1 km wide plateau located at 950–1050 m a.s.l., 890–990 m above the valley bottom. The largest outlined instability corresponds to a volume estimated at 50–200 Mm$^3$ (Braathen et al., 2004), and even at 300 Mm$^3$ (Dahle et al., 2011). Three smaller unstable parts were highlighted (Dahle et al., 2011) (Fig. 2) and periodic dGNSS measurements (2003–2012) confirm significant horizontal and vertical displacements at these locations, with 3D rates between 5 and 14 mm/year (Oppikofer et al., 2013).

Structural analyses (Braathen et al., 2004; Saintot et al., 2011a, 2012), TLS (Longchamp et al., 2010), run-out modelling and risk assessment (Dahle et al., 2011), periodical dGNSS measurements (Oppikofer et al., 2013) and GB-InSAR surveys were performed (locations in Fig. 4).

From the field campaigns, it appears that the plateau is affected by large subvertical fractures with dip direction to N-NE/S-SW. A subvertical foliation with a dip direction to ENE/WSW highly contributes to shape the edge of the plateau. A flat-lying joint is also identified and explained the development of the instability by a sagging mechanism along flat-lying discontinuities and opening along the vertical sets (Braathen et al., 2004; Saintot et al., 2011a, 2012). The results from the Coltop3D analysis based on 2008 TLS dataset (Longchamp et al., 2010) highlight overall the same elements (Fig. 3, b), J6' corresponding most likely to the foliation plane and J1 as flat-lying set. Results from 1 m ALS DEM are also presented in Fig. 3 (c) and highlights overall the same sets of discontinuities (with some variations of the dip angles as a probable effect of the lower spatial resolution) (Rouyet, 2013).

Due to fewer signs of activity and lower estimated probability of failure than for Mannen, fewer investigations were carried out on the plateau and no continuous monitoring is implemented.

### 3. Data & methods

#### 3.1. GB-InSAR

The current versions of GB-InSAR systems use generally a C, X or Ku frequency band. The measuring head including transmitting and receiving antennas moves along a 2–3 m long rail in order to synthetize the SAR images (Luzi, 2010). Details about the available systems and their characteristics are available in recent reviews (Monserrat et al., 2014; Caduff et al., 2014). The present research analyses data acquired by LiSALab GB-InSAR systems (Ellegi Ltd.). It uses a Ku frequency band (central frequency: 17.2 GHz; wavelength: 17.44 mm). The range resolution (depending on the bandwidth) is between 0.5 and 3 m and the azimuth resolution (depending on the rail size and the range) can reach 1.5 m at 500 m. This system allows displacement rates from mm/year to a few m/day to be measured in near-real time, and up to 4 km away from the sensor. It has to be noted that only 1D displacements along the line-of-sight (LOS) can be detected. This leads to potential underestimation of the displacement if the LOS is oblique in respect to the real displacement vector.

In early 2010, a permanent GB-InSAR system was installed in the valley to continuously monitor Mannen rockslide (location: Fig. 4, red...
The distance to the backscarp is about 2100 m along the LOS. The LOS has a SW orientation and a mean view angle (between the beam and horizontal) of 35°.

In addition, a second station for intermittent GB-InSAR measurements of Børa area was built in summer 2011 (location: Fig. 4, yellow star B). Two campaigns were carried out at the station B, during 15 days in August (10.08–24.08.2011) and 28 days in September–October (21.09–18.10.2011). In 2012, a new campaign was performed during 21 days (19.06–09.07.2012). The objective was to get information about displacements in Børa area and create a data overlap with the permanent GB-InSAR system in order to check the reliability of the results. The distance along the LOS to the top of the slope is about 2000 m. The LOS has a SW orientation and a mean view angle of about 31°.

The main measurement parameters of the two GB-InSAR systems can be found in the Table 1. Pictures of the two stations and their measuring views are presented in Fig. 5 and the main coherent areas for the two sensors are displayed in Fig. 4. For sake of simplification, Fig. 4. Location of ground-based monitoring devices (in situ and GB-InSAR), coherent areas for GB-InSAR systems (here using 0.7 filter applied on 10–16.08.2011 interferogram). Background: 0.2 m orthophoto 2006.

Table 1
Summary of main GB-InSAR acquisitions parameters for the two available systems.

<table>
<thead>
<tr>
<th>GB-InSAR parameters</th>
<th>Station A</th>
<th>Station B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acquisition dates</td>
<td>02.2010–now (Continuous)</td>
<td>10.08–24.08.2011</td>
</tr>
<tr>
<td></td>
<td></td>
<td>21.09–18.10.2011</td>
</tr>
<tr>
<td></td>
<td></td>
<td>19.06–09.07.2012</td>
</tr>
<tr>
<td>Maximum range</td>
<td>2700 m</td>
<td>2400 m</td>
</tr>
<tr>
<td>Range resolution</td>
<td>1.9 m</td>
<td></td>
</tr>
<tr>
<td>Azimuth resolution</td>
<td>7.8 m at max. range 1.5 m at 500 m 6.9 m at max. range 1.5 m at 500 m</td>
<td></td>
</tr>
<tr>
<td>Azimuth width</td>
<td>2200 m</td>
<td></td>
</tr>
<tr>
<td>Central frequency (wavelength)</td>
<td>17.2 GHz (17.44 mm)</td>
<td></td>
</tr>
<tr>
<td>Bandwidth</td>
<td>80 MHz</td>
<td></td>
</tr>
<tr>
<td>Number of freq. points</td>
<td>2001</td>
<td></td>
</tr>
<tr>
<td>Synthetic aperture</td>
<td>3 m</td>
<td></td>
</tr>
<tr>
<td>Number of steps inside the aperture</td>
<td>751</td>
<td></td>
</tr>
<tr>
<td>Acquisition time</td>
<td>8 min</td>
<td></td>
</tr>
<tr>
<td>Revisiting time</td>
<td>10 min</td>
<td></td>
</tr>
</tbody>
</table>

* Campaign partly affected by snow.
Fig. 5. Left: Pictures of the two GB-InSAR stations. A: Permanent GB-InSAR station, B: Station for intermittent GB-InSAR measurements; Right: Respective views from the stations (Rouyet/Derron, 20.08.2012). Acquisition parameters in Table 1 and locations in Fig. 4.

Fig. 6. Satellite InSAR mean coherence map from Multi-year Stacking method using TSX/TDX satellite InSAR data from ascending geometry (geocoding resolution: 10 m × 10 m). Areas in orange and red are respectively affected by layover and shadow effects.
the two stations will be thereafter named station A (permanent GB-InSAR) and station B (intermittent GB-InSAR measurements). In 2014, two new radar positions were built to carry out periodic measurements, but will not be included in this paper.

Images acquired from station A were processed in order to get information about displacements over one year in 2011–2012 (cf. Section 4.1.1). Because of the coherence loss during the winter season due to snowfall, the reference periods were chosen in June. Datasets from the campaigns at the station B were also analysed. The results presented in Section 4.1.2 correspond to the first 2011 campaign and the 2012 campaign. The second 2011 campaign did not highlight significant displacements and was partly affected by snowfall. Images acquired from the station A at the same periods were also analysed and the results compared with those of the station B. Using the large dataset acquired at the station A, time series at specific locations between February 2010 and December 2012 were extracted and are analysed in Section 4.1.3.

The GB-InSAR data were processed using LiSALab software (Ellegi srl.). The results are $3 \times 3$ multilooked and analysed using a 0.7 coherence filter.

A radar image is acquired every 10 min, but for comparisons 24 h-averaged images were used. This kind of data requires a procedure to remove the atmospheric component (e.g. Caduff et al., 2014; Kristensen et al., 2013). This has been performed by combining the 24 h-averaging and a supervised approach by manually selecting reference regions. The averaging contributes to reduce significantly the noise and phase component related to turbulent atmosphere. The supervised approach allows residual atmospheric disturbances to be corrected by selecting areas without any evidence of significant ground deformation. Different areas have been tested by different operators and do not show significant variations on the main areas of interest (<1 mm). In Mannen/Børa final results, the main moving areas show clear spatially and temporally progressive trends. In the overlapping area, they are detected by both GB-InSAR systems using two independent processing.

In Figs. 8–11 (cf. Section 4.1), negative values correspond to movements toward the sensor (distance shortening along the LOS); positive values correspond to movements away from the sensor (distance increasing along the LOS). For sake of simplification and reader convenience, they are expressed thereafter as downward/upward displacements.

### 3.2. Satellite InSAR

In addition to GB-InSAR data, satellite InSAR images acquired by TerraSAR-X/TanDEM-X (TSX/TDX) sensors (Airbus Defense & Space - Infoterra GmbH) were processed. The satellites use a X band (central frequency: 9.6 GHz; wavelength: 3.11 cm) and have a repeat-pass time interval of 11 days. The dataset was acquired with a StripMap mode and from an ascending orbit (LOS orientation: 75.2°N, incident angle: 21.4°) in order to get reduced geometrical distortions on east-facing slopes. The LOS and the land cover provide a good coverage of the plateau and the upper part of the slope. The bottom part of the slope is partly masked out due to vegetation inducing low coherence and layover effect from the other side of the valley (Fig. 6). Due to loss of coherence in case of snowfall, only 24 snow-free scenes between

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**Table 2**

Summary of characteristics of satellite data and processing parameters.

<table>
<thead>
<tr>
<th>Satellite data characteristics</th>
<th>Satellite</th>
<th>Band</th>
<th>Dataset</th>
<th>Time period</th>
<th>Repeat-pass interval</th>
<th>Number of images</th>
<th>Track angle (LOS orient.)</th>
<th>Incidence angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>TSX/TDX</td>
<td>X (λ:3.11cm)</td>
<td>StripMap Ascending</td>
<td>07.2010 – 10.2013</td>
<td>11 days</td>
<td>24</td>
<td>-14.81° (75.2°N)</td>
<td>21.4°</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>InSAR processing parameters</th>
<th>Processing type</th>
<th>Multilooking (range x azimuth resolution)</th>
<th>Max. spatial &amp; temporal baselines</th>
<th>Generated interfer.</th>
<th>Selected interfer.</th>
<th>SBAS spatial &amp; temporal filters</th>
<th>Pixel selection (coh. &amp; fraction of image thr.)</th>
<th>Calibration point (UTM 32N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multi-years Stacking</td>
<td>Factors: 3 x 4</td>
<td>600 m / 88 d</td>
<td>69</td>
<td>57</td>
<td>-</td>
<td>0.4 &amp; 0.6</td>
<td>692508 / 436468</td>
<td></td>
</tr>
<tr>
<td>2013 SBAS</td>
<td>8.3 m x 8.3 m</td>
<td>35</td>
<td>27</td>
<td>500 m / 44 d</td>
<td>0.4 &amp; 0.6</td>
<td>(GPS 1 stable)</td>
<td></td>
<td>692508 / 436468</td>
</tr>
</tbody>
</table>

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Please cite this article as: Rouyet, L., et al., Evidence of rock slope breathing using ground-based InSAR, Geomorphology (2016), http://dx.doi.org/10.1016/j.geomorph.2016.07.005
July 2010 and October 2013 were used (Fig. 7). The satellite data characteristics are summarized in Table 2 (top).

The results presented thereafter as maps were obtained using a simple stacking of interferograms with small spatial (max. 600 m) and temporal (max. 88 d) baselines. This allows a large amount of interferograms from disconnected seasons to be processed together in order to reduce atmospheric effects and other noise sources (Zebker and Villasenor, 1992; Zebker et al., 1997; Gabriel et al., 1989). A second processing using only the interferograms from 2013 has been performed in order to get one connected set and be able to apply Small Baseline Subset (SBAS) method (Berardino et al., 2002; Lauknes et al., 2011). This allows the time series presented in Section 4.2 to be retrieved.

The processing was performed using the Norut developed GSAR software (Larsen et al., 2005), using the national 10 m DEM (provided by Kartverket) to remove the topographic component. The InSAR processing parameters can be found in Table 2 (bottom). The numbers of generated interferograms depend on the chosen spatial/temporal baselines thresholds (column 4, InSAR processing parameters, Table 2) and a second manual selection is performed to remove interferograms affected by low coherence, significant atmospheric effects or obvious unwrapping errors (column 5, InSAR processing parameters, Table 2).

In Section 4.2 (Figs. 12–13), in order to have a straight-forward comparison with GB-InSAR results, signs convention is inverted from the LOS-logic: negative values correspond to movements away from the satellite (downward) and positive values correspond to movements toward the satellite (upward).

4. Results

4.1. GB-InSAR results

4.1.1. One year displacements on Mannen rockslide

The velocities recorded along the LOS between June 2011 and June 2012 reached 18 mm/year toward the GB-InSAR in the upper part of Mannen rockslide (Fig. 8). This is overall consistent with in situ data that show 23 mm/year with a main vertical component for DGPS3 and 18 mm/year for the laser-reflectors (Fig. 8, pink elements). A clear velocity contrast is noticeable between the upper southern part of the instability A and the rest of instabilities A and B. During this time interval, 7 mm toward the GB-InSAR is measured on the lower southeastern part. In the lower northern part, mainly horizontal displacements toward the north are recorded by DGPS. Due to an oblique LOS relatively to the displacement vectors, the GB-InSAR is not able to capture a significant part of the movement in this area. No information is available in Fig. 8.
the western part of instability B located in a shadow area. In order to overcome these problems, a new station for intermittent GB-InSAR campaigns was set up further northwest, and measurements started in September 2014 (Skrede et al., 2015).

4.1.2. Intermittent Børa campaigns & corresponding Mannen results

During the first Børa campaign in August 2011, considering the interval 10.08–23.08.2011 (14 days), no significant movement was detected on Mannen rockslide using GB-InSAR (station A). This is overall consistent with the in situ data, which show that main periods of movements occurs during the thawing period earlier in the season. On Børa, the results of the station B highlight a slight downward trend in the northwestern upper part that can be ascribed to residual atmospheric effects, but several fast moving small sectors are detected in active rockfall areas in the southeastern part of the dataset. Displacements are also detected in the lower part on debris cones affected by active torrential processes and significant erosion/deposition cycles.

The main interesting element is located in the overlapping part of the two GB-InSAR datasets (cf. Fig. 4). During August campaign in 2011 an increase of sensor-to-target distance is detected, corresponding to upward displacements. The displacements exceed 8 mm in 13 days (Fig. 9, top). In July 2012, this moving part is again clearly distinguishable, but this time the movements are inversed (shortening of sensor-to-target distance, i.e. downward displacements). The highest displacement rate is reached during 07.09–09.07.2012 interval (up to 8 mm in 2 days) (Fig. 9, bottom). For both campaigns at the station B (August 2011 and June–July 2012), GB-InSAR results are consistent with station A in the overlapping part, and the georeferenced results

**Fig. 10.** Comparison of time series from GB-InSAR A & B at P1–P2 locations. Top: First campaign at the station B (10.08–23.08.2011). Bottom: 2012 campaign at the station B (19.06–9.07.2012) (points locations in Fig. 9).
show a good spatial fit of the two datasets (Fig. 9). The moving part is well delineated and affected an area of approximately $1 \times 0.5$ km².

Time series are generated at two locations (P1 and P2) where coherent information is available for both GB-InSAR systems, in the overlapping part of the two datasets (Fig. 10, point locations in Fig. 9). The data are in the respective LOS for each GB-InSAR system. They confirm the upward trend in August 2011 (Fig. 10, top). For both points, maximal displacements are reached after 9 days. The measurements show a relative stability the next 5 days. The two GB-InSAR systems provide measurements in good agreement (overall same rate of movement and variations). In June–July 2012, the time series confirm the movement inversion and the consistency of both datasets (Fig. 10, bottom). The time series show two main stages of acceleration during 21.06–26.06.2012 (7 mm in 5 days) and 06.07–09.07.2012 (7 mm in 3 days).

4.1.3. Inter-annual results

Using the whole GB-InSAR dataset acquired at the station A since February 2010 to the end of 2012, significant variations are confirmed in the southeastern part (overlapping part with GB-InSAR B). Similar

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![Figure 11](image_url)
Fig. 12. Multi-years Stacking results using 2010–2013 TSX/TDX satellite data from ascending geometry (geocoding resolution: 10 m × 10 m). Black arrow: LOS, black star: calibration point. Background: hillshade from 1 m DEM. Top: Overview with location of zoom (white rectangle). Bottom: Zoom on Mannen rockslide and area affected by rock slope breathing. Blue stars: location of SBAS time series presented in Fig. 13.

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trends are visible in the northwestern part of the monitored area but with lower amplitude (P4–P5) (Fig. 11, point locations in Fig. 9). The movement cycles have a seasonal recurrence. In 2010, 2011 and 2012, movement inversions occur abruptly between June and July (from downward to upward displacements) and the fastest upward peaks occur every year between mid-June and August (vertical dashed lines, Fig. 11). For P2, the upward displacement reaches 13 mm in 72 days in summer 2011. From the meteorological data (Fig. 11, graphs on the right. Station at the top of Mannen, cf. Fig. 4), it is possible to see that the downward trend is clearly related to the thawing period and its duration is affected by the abruptness of the transition (short duration and sharp transition in 2011 vs longer duration and smoother transition in 2012). This inflation/deflation phenomenon, hereafter so called rock slope breathing, is discussed more into details in Section 5.2.

4.2. Satellite InSAR results

The TSX/TDX multi-years Stacking processing using maximal temporal baselines of 88 days (cf. Table 2) shows rate of movement up to 40 mm/year and 58 mm/year downward (distance increasing along the LOS) recorded for some small sectors in the upper part of the instabilities A and B, while the main moving area has values between 15 and 25 mm/year (Fig. 12). It has to be noted that the results expressed in annual mean velocity correspond to an extrapolation of the snow-free seasons (no inter-annual interferogram). Large displacements during these periods can thus lead to an overestimation of the values.

In the southwestern part of the instability B (Veslemannen), movements are detected. Previously this area was not documented by ground-based instruments, but after significant movements and acceleration were measured by GB-InSAR in September–October 2014, extensometers and geophones were installed at this location and an automatic LiDAR system was put in the valley. The Veslemannen site is now closely monitored (Skrede et al., 2015). In the southeastern part (Børa), some displacements are also detected, especially in the lower part (debris cones affected by torrential processes and erosion/deposition cycles).

The area subjected to rock slope breathing in the overlap of the GB-InSAR datasets is not totally well documented by TSX/TDX satellites due to the lower coherence downslope. The LOS of the sensor can also lead to potential misestimating of displacements in the area due to oblique or even perpendicular view in respect to the real vectors. However, mean rates up to 28 mm/year downward are detected from the Multi-year Stacking processing. Thanks to SBAS method using interferograms from 2013, it is also possible to retrieve time series between July and October 2013. Results at different locations on the area affected by rock slope breathing are presented in Fig. 13 (top). For sake of comparison and reliability check, other time series from the plateau (supposed as stable) and on Mannen rockslide can be seen in Fig. 13 (bottom). The locations of the selected points are displayed on the zoom in Fig. 12 (bottom). The results highlight three different clear trends: 1) round

Fig. 13. SBAS time series in snow-free season 2013 (point locations: Fig. 12). Top: B1–4 on area affected by rock slope breathing. Bottom: Others examples of time series on the plateau and on Mannen rockslide. Note the difference of scale in y-axis.

Please cite this article as: Rouyet, L., et al., Evidence of rock slope breathing using ground-based InSAR, Geomorphology (2016), http://dx.doi.org/10.1016/j.geomorph.2016.07.005
zero displacements on the plateau, 2) quite linear displacements on the rockslide to 18 mm in 3 months, 3) small displacements with inversions in August on the area affected by rock slope breathing, that confirm the GB-InSAR results.

5. Discussion

This section is organized in two parts. In Section 5.1, the results from available measuring systems (GB-InSAR, in situ and satellite InSAR) are summarized and main findings about the spatial distribution of movement rate are described. As main focus of the article, the rock slope breathing phenomenon and the current assumptions about the factors explaining this effect are discussed in Section 5.2.

5.1. Mannen rockslide & Børa plateau

The combined results of GB-InSAR, in situ and satellite InSAR contribute to have a good overview of the Mannen rockslide behaviour and affine the extents of the different instabilities especially in hard-to-access steep slopes. Overall the results are consistent and complementary. They allow the area to be divided in three parts:

1) A main active part in the upper southern part of the instabilities A. It is documented by DGPS 3 (23 mm/year in 2011), two lasers-reflectors (to 18 mm/year in 2011), the extensometer 2 located in the backcrack (44 mm/year in 2011), GB-InSAR data (to 18 mm/year between June 2010–2011) (Fig. 8) and TSX/TDX satellite InSAR (to 40 mm/year) (Fig. 12). According to DGPS results, this moving area has a main vertical component and a northeast horizontal orientation.

2) A second active part in the upper western part of the instability B (Veslemannen), not documented by in situ but highlighted by satellite data (to 58 mm/year) (Fig. 12), and recently by the new 2014 GB-InSAR station (Skrede et al., 2015).

3) A slower part including the other in situ devices. The DGPS highlighted rates of displacement between 7 and 13 mm/year in 2011, the GB-InSAR data velocities to 6 mm/year (Fig. 8) and 10 mm/year for satellite InSAR (Fig. 12). The especially low values recorded by GB-InSAR can be explained by an oblique LOS orientation in respect to the movement orientation documented by the DGPS (main horizontal component with a north orientation).

At Bora, GB-InSAR system did not highlight significant moving patterns during the intermittent campaigns, except in the area discussed in Section 5.2. No clear deformation patterns are measured by GB-InSAR at the locations of three identified small instabilities in Bora (Fig. 2). In these sectors, significant displacement rates were measured by periodic dGNSS measurements between 2003 and 2012 (Oppikofer et al., 2013). However, the mean annual rates revealed by dGNSS are between 5 and 14 mm/year, which explain the difficulty to be highlighted by GB-InSAR during short-term intermittent campaigns. GB-InSAR detected nevertheless some small sectors along the upper steep part of the slope and on debris cones downslope (Fig. 9). This seems consistent with the satellite InSAR results which highlight also some localized moving areas (Fig. 12).

5.2. Rock slope breathing

The GB-InSAR campaigns at station B highlighted the presence of an area subjected to variations of movement in the overlapping part with the data from the continuous GB-InSAR system (station A). The
Fig. 15. Simplified 3D models of Mannen/Børa summarizing the geometries of the remote sensing systems, the main geological structures and discussing the rock slope breathing effect. Background: 0.2 m orthophoto 2006.
seasonal effects related to temperature (Gischig et al., 2011), precipitation and groundwater (e.g. Amelung et al., 1999; Schmidt and Bürgmann, 2003; water loading (e.g. Zangerl et al., 2008; Strozzi et al., 2011). Using satellite InSAR, measurements from TSX/TDX satellite data confirm these variations.

Looking at the location map (Fig. 14, top right), we can see that this part is located below the two Kråkenesvatna lakes. These lakes have no visible outlets, but at their northern edge, a siphon phenomenon can be observed during the summer (Fig. 14, D). This testifies a strong water infiltration in this area. Tracing tests from Kråkenesvatna lakes were performed in October 2007 and concluded to a complex drainage system involving multiple pathways of water in the rock mass. The measurements at 19 source locations in the valley revealed indeed that the peaks of responses curves are multiple and vary between 3 and 10 days according to the location (Kvakland, 2009). Considering the time of transit through the rock mass the assumption of rock slope breathing caused by variations of groundwater charge is likely. The order of magnitude of 10 days fits well with the variations detected from GB-InSAR (Fig. 11). In Fig. 9, we can moreover see that the moving area is located just below and between the main delineated instabilities. It probably contributes to a convergence/concentration of groundwater from the large fractures at the basal and lateral edges of the unstable areas. Thus, the current assumption to explain the displacements measured by GB-InSAR is that the area is subjected to large variations in groundwater pressure. At the beginning of the thawing season, an increase of charge due to high water infiltration and possible presence of residual ice in fractures lead to millimetric inflation of the rock slope, and thus downward displacements. During the summer, the re-distribution of water inputs and complete melting of residual ice in fractures make possible a water evacuation and desaturation of the slope, which leads to a deflation, and thus upward displacements. The assumption is represented as simplified schemes in Fig. 15. The displayed structures are based on the approximate results of TLS/ALS analysis using Coltop3D software (Fig. 3).

The remotely measured phenomenon highlights the need of further research in order to document and understand the rock slope breathing. Seasonal variations can indeed have an impact on the significance of periodic displacement measurements and induce errors in the estimation of mean velocities (under-/overestimation of the values if the measurements are performed at wrong periods). In order to evaluate correctly the deformation rates of unstable areas and integrate relevant information in hazard classification systems (Hermanns et al., 2012, 2013a), seasonal trends have to be known and taken into account.

The rock slope breathing can moreover have a long-term effect on rock slope stability. In research on landslides, role of groundwater variations is well known and considered in term of pore pressures variations affecting the factor of safety (e.g. Collins and Znidaric, 2004; Eberhardt et al., 2007). Effects of water table level fluctuations inducing subsidence and uplift of rock mass were studied to explain deformation related to tunnelling and hydroelectric infrastructure (e.g. Zangerl et al., 2008; Strozzi et al., 2011). Using satellite InSAR, water loading fluctuations inducing land subsidence and uplift rebound were detected, but they are mainly related to cases of excess pumping of groundwater (e.g. Amelung et al., 1999; Schmidt and Bürgmann, 2003; Chen et al., 2007; Reeves et al., 2011). In case of rock instabilities, seasonal effects related to temperature (Gischig et al., 2011), precipitations, snow-melting (Coe et al., 2003) and/or freeze-thaw (Nordvik et al., 2010; Bilka and Christiansen, 2014) have also been measured using conventional or/and remote-sensing methods. These studies focus usually on the understanding of the triggers and controlling factors of the instabilities.

The elastic or semi-elastic behaviours of the rock mass associated to ground water variations and potential fatigue mechanism related to these cycles are still not well covered in geohazards studies, although mentioned in several papers (e.g. Jaboyedoff et al., 2009; Mazzanti and Brunetti, 2010; Salvini et al., 2015). The progressive weakening and degradation of rock mass from repeated (e.g. seasonal) fluctuations of stresses related to hydrogeological cycles can be referred as hydromechanical fatigue. Its contribution to rock slope deformation has been further analysed and discussed in Cappa (2006), Preisig et al. (2016) and Gischig et al. (2016). Based on field experiments and simulations of relations between fluid pressures and displacements, Cappa (2006) performed a sensitivity study showing that the hydraulic aperture, the stiffness and the network geometry of the fractures are key parameters of hydromechanical processes in a fractured rock mass. In addition, the temporal shift in the pressure-deformation response and the impact of local heterogeneities are highlighted and contribute to the complexity of the processes. Preisig et al. (2016) and Gischig et al. (2016) showed in addition that hydromechanical fatigue is effective when high degree of damage pre-exists in the rock mass. Due to its gradual and multi-factors nature, the phenomenon has to be considered at several spatial and temporal scales and require advanced modelling techniques. For further work, applying principles of Biot’s theory of poroelasticity (Biot, 1955) seems to be the most relevant approach to model this complex fluid-to-solid coupling behaviour (Wang, 2000).

In this context, our research does not claim to explain the hydromechanical processes involved in Mannen/Børa rock slope but provides new measurements that evidence a breathing phenomenon and shows that remote sensing techniques can contribute to detect, map and monitor small-scale movement fluctuations due to water pressure in natural slopes.

6. Conclusion & prospect

The Mannen/Børa rock slope is an interesting case study due to the availability of two GB-InSAR systems imaging the same rock slope. They cover a large stretch of the slope and a slight data overlap allows the reliability of the results to be checked. They have the advantage to provide information on the weakly monitored Børa plateau and in steep mid-slope where in situ devices are difficult to install. Thanks to GB-InSAR large coverage, high temporal frequency, high resolution and accuracy, an approximately 1 × 0.5 km² sector subjected to millimetric variations and inversion of movement (inflation/deflation) has been highlighted. Satellite InSAR time series from TSX/TDX data confirm these variations. Analysing the large GB-InSAR dataset from the continuous station A, this rock slope breathing is proved to have a seasonal recurrence. The phenomenon is ascribed to hydrogeological variations.

In addition and in order to overcome some limitations of GB-InSAR technique (1D measurements along the LOS, intermittent campaigns, atmospheric effects removing, coherence loss, etc.), analyses of in situ monitoring data and satellite InSAR were performed. The combination of in situ measurements, terrestrial and space borne remote sensing provides a large amount of complementary information. In this way, the edge and velocities of the main Mannen unstable areas can be better defined.

These preliminary results highlight the need for further research in this site, which can be summarized in two parts. Firstly, further investigations are required to fully understand the hydrogeological processes and the subsurface structures of the rock slope, especially to understand the rock slope breathing phenomenon and confirm the assumption of the water pressure influence. This includes further investigations combining surface and subground data to depict its complex geometry. In order to better understand and constrain the behaviour of the rock masses in the area stress-strain numerical analysis should be performed and included in further models. Secondly, a complete and systematic analysis of the large GB-InSAR dataset from station A, as well as a more complete integration with the other GB-InSAR (intermittent measurements from station B and new 2014 stations), in situ and satellite InSAR results would be valuable to provide information about movement directions and contribute to confirm the likelihood of mechanisms. This could overcome the intrinsic limitation of InSAR...
Acknowledgments

The research would not have been possible without the great job of the team working at the NVE monitoring center in Stranda. Thanks to the intensive work of each member of the crew, impressively huge and exciting datasets from the performant monitoring network of Mannen/Børa are available for research. Many thanks also to LiSALab team (Ellegi Ltd.) and especially Carlo Rivolta for his support during GB-InSAR data processing. The TerraSAR-X data has been provided by the German Aerospace Center (DLR) under the TSX-AO project contract #GE00764. In addition, we acknowledge the works of the landside group of the Geological Survey of Norway (NGU) that contribute to better understand geometry and behaviour of rock instabilities in Romsdal valley. The authors wish finally to thank the two anonymous reviewers and Reginald Hermans for their valuable comments to improve this paper.

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