Q. 102 – R. 26

COMMISSION INTERNATIONALE
DES GRANDES BARRAGES

VINGT SIXIÈME CONGRÈS
DES GRANDS BARRAGES
Vienne, Juillet 2018

REMOTE SENSING BASED MONITORING OF RESERVOIR SLOPES*

Christine FEY
TIWAG, TIROLER WASSERKRAFT AG AND ALPS GMBH

Sebastian PERZLMAIER
TIWAG, TIROLER WASSERKRAFT AG

Volker WICHMANN
ALPS GMBH AND LASERDATA GMBH

AUSTRIA

SUMMARY

Remote sensing techniques are more and more used for comprehensive deformation monitoring and supplement conventional point based geodetic measurement methods. In this study, the past and ongoing deformation behaviour of a rock glacier in the vicinity of a reservoir is monitored by imagery and laserscan data. Rock glaciers are geomorphological phenomena of mountain permafrost which slowly move downslope as a consequence of the ice deformation. We used historic ortho-images from national and federal archives, which enable the reconstruction of past deformations since the 1970s. The ongoing monitoring is performed with a terrestrial laser scanner (TLS) from 2014 onward. The combination of terrestrial laser scanning (TLS) data with already acquired airborne laser scanning (ALS) data provides deformation results directly after completion of the first TLS field campaign. In contrast to geodetic point measurements, deformation measurements based on imagery and laser scanning data is not suited to detect sub centimetre deformations. But the spatial information obtained from remote sensing allows analyses of the spatio-temporal evolution of the rock glacier. The

* *Surveillance des versants de retenue avec des techniques de télédétection*

analysis shows that the tongue zone of the rock glacier accelerated since the beginning of the 21th century. This acceleration is in accordance with studies of other alpine rock glaciers and caused by increasing permafrost temperatures. The main flow direction of the rock glacier tongue is parallel to the reservoir and the tongue ends in a flat depression. The data document that the rock glacier has no relevant impact on the reservoir. The methods for retrospective deformation monitoring and on-going monitoring presented in this study are applicable to other study sites and deformation processes (e.g. rock fall, rock slides).

Keywords: Finstertal Dam, Deformation Measurement, Monitoring, Geological Investigation, Landslide, Reservoir Slope, Slope Stability.

RÉSUMÉ

Des techniques de télédétection sont de plus en plus utilisées pour la surveillance de la déformation extensive et peuvent ajouter les mesures classiques géodésiques à base de l'observation des points seuls. Dans cette étude, la déformation passée et en cours d'un glacier rocheux à proximité d'un réservoir est contrôlée par les données ortho-images et laserscan. Des glaciers rocheux sont des phénomènes géomorphologiques du pergélisol de montagne qui se déplacent lentement vers le bas en raison de la déformation de la glace. Nous avons utilisé des ortho-images historiques des archives nationales et fédérales, qui permettent la reconstruction des déformations passées depuis 1970. La surveillance continue est réalisée avec un scanner laser terrestre (TLS) à partir de 2014. La combinaison du données laser terrestre (TLS) avec données laser aéroporté (ALS) déjà acquis, donne des résultats de déformation directement après la première campagne de terrain TLS. Contrairement aux mesures du point géodésique, les mesures de déformation basées sur l'ortho-image et les données laser ne sont pas appropriées pour détecter les déformations en ordre de grandeur de centimètre. Mais l'information spatiale obtenue par télédétection permet des analyses de l'évolution spatio-temporelle du glacier rocheux. Les analyses montrent que la zone langue du glacier rocheux accélère depuis le début du 21ème siècle. Cette accélération corresponde aux études des autres glaciers rocheux alpins et est causée par l'augmentation de la température du pergélisol. La direction du flux principal de la langue du glacier rocheux est parallèle au réservoir et la langue se termine dans un plat creux. Les observations documentent que le glacier rocheux n'a aucune influence pertinente sur le réservoir. Les méthodes de surveillance de la déformation rétrospective et continuée présentés dans cette étude sont applicables aux autres sites d'étude et aux autres processus de déformation (p. ex. chutes de pierres, éboulements).

Mots-clés: Finstertal Barrage, Mesure de Deformation, Auscultation, Geologie, Glissement de Terrain, Versant de Retenue, Stabilite de Versant.

1. INTRODUCTION

Monitoring plays an important role in dam safety. Monitoring allows quantifying the impact on a structure and should give evidence that the behavior of the structure is within expectations. Elsewise it should indicate trends against unexpected behavior timely. These principles are also valid for reservoir slopes. Traditionally, reservoir slopes are monitored by geodetic single point measurements. The monitoring is important to detect unexpected slope deformation behaviour at an early stage.

Remote sensing techniques are more and more used for comprehensive deformation monitoring and supplement conventional point based geodetic measurement methods. Remote sensing data gives spatial information about slope deformation and is suited to distinguish between slope parts with different activities and to delineate the deformed slope parts from stable ground.

In the last two decades, increasing computing capabilities and innovations in sensors and global positioning systems favoured a rapid development of the laser scanning technique [1]. Campaigns of airborne laser scanning (ALS) supplemented national and federal topographic imagery surveying. Until recently, topographic data acquisition by laser scanning was limited to companies specialized on airborne data acquisition. The rapid development of portable long-range terrestrial laser scanners (TLS) [2] and the decreasing purchase costs for unmanned aerial vehicles (UAV), in combination with innovations in Structure from Motion (SfM) and Multi-View Stereo (MVS) photogrammetry algorithms (e.g. [3], [4]), favours topographic data acquisition by users from various disciplines (e.g. geometers, archaeologist, architects, geomorphologists etc.). This allows shorter response times to sudden events (e.g. rockfall) and provides the possibility to increase the temporal resolution by repeated measurements. Both TLS and UAV based monitoring is applicable in rough mountain terrain and provides detailed 3D point clouds on demand. The rapid progress in computer science favoured not only the development of new sensors for data acquisition. Increasing computing capabilities enabled the processing of images from past aerial imaging campaigns. Archives of aerial imagery data from national and federal survey campaigns from the last century are available in most European countries. For some regions aerial imagery is available since the 1950s. Analyses of data pairs from archives of different epochs allow the reconstruction of past geomorphological and geological processes (e.g. landslide development, rock glacier creep, glacier retreatment etc.) and anthropogenic processes (e.g., constructions) [5].

In this study, we demonstrate the opportunities provided by remote sensing for retrospective and ongoing slope deformation monitoring. Remote sensing methods are applied to analyse the past and ongoing deformation behaviour of a rock glacier in the vicinity of a reservoir. The reconstruction is based on orthoimages and ALS data from national and federal imaging campaigns in combination with terrestrial laser scanning (TLS) data from on-going monitoring campaigns.

The deformation monitoring methods were developed in the frame of the alpS-K1-Centre research project 'adapt Infra' which is supported by TIWAG and by the 'COMET' program managed by the FFG.

2. STUDY SITE

Finstertal is the upper stage reservoir of the TIWAG Sellrain-Silz Group located in the Tyrol, Austria. The 150 m high rockfill dam was built 1977-1980 and forms a reservoir of 60 Mio. m³. The reservoir is surrounded by stable rock slopes of orthogneis with only little overburden of stable talus material. The monitoring of the reservoir slopes is limited to the annual observation of some survey points (Fig. 1). About ten years ago the survey point 106 (Fig. 1) showed a deformation in the range of 0.005 m/a. The survey point is located at the eastern shore of the

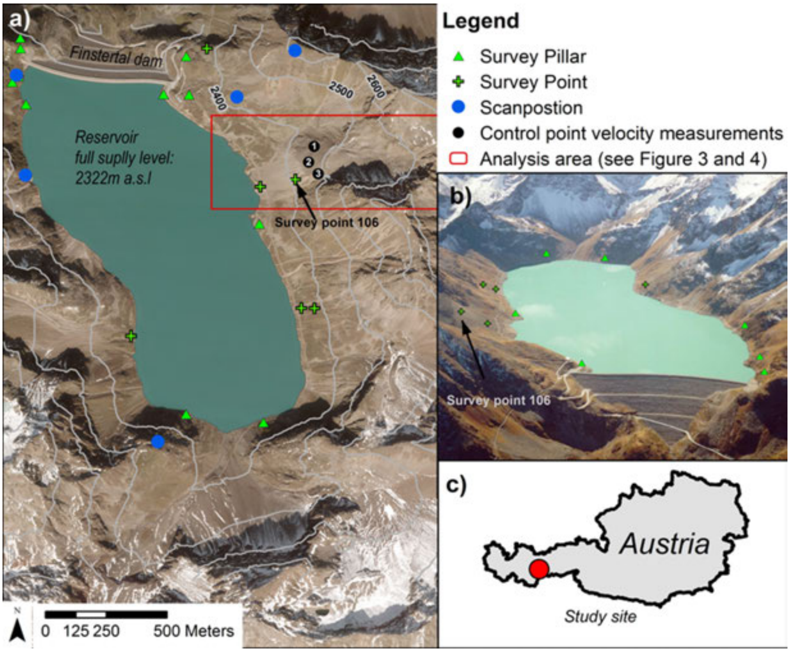

Fig. 1
a) Ortho and b) oblique view of the Finstertal dam
and reservoir and c) location of the study site in Auistria
a) Ortho photographie et b) l'avis du barrage et du réservoir de Finstertal et
c) localisation de la zone de étude en Autriche

reservoir on a non-vegetated talus slope which interrupts the high alpine meadows. The talus slope is part of the front slope of a rock glacier. Rock glaciers are lobate or tongue shaped geomorphological phenomena of mountain permafrost. They consist out of frozen debris and rocks in interstitial ice and slowly move downslope as a consequence of the ice deformation [6]. Rock glaciers either have their origin in debris covered glaciers (ice-cored rock glaciers) or are solely permafrost phenomena (ice-cemented rock glaciers) [7]. The Finstertal rock glacier is a lobate shaped rock glacier with a length of about 580 m and a width between 120 m and 250 m. Its rooting zone (Fig. 2) is located at about 2.600 m a.s.l. within a small cirque surrounded by steep north facing walls, which are

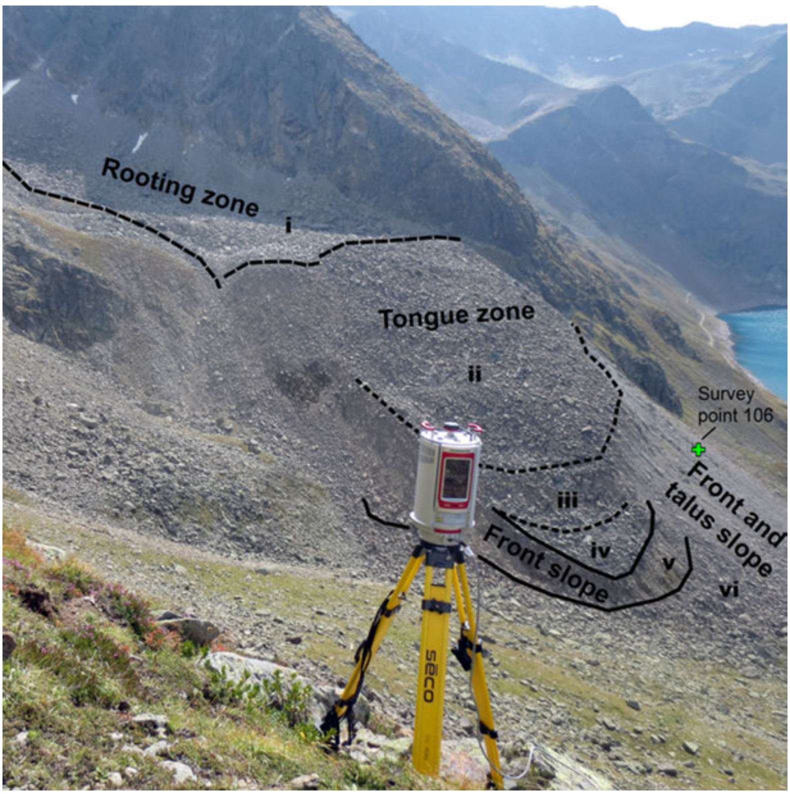

Fig. 2
Observed rock glacier and the used terrestrial laser scanner
(numbers indicate different activity zones, see results section)
Glacier rocheux observée et appareil TLS utilisé
(les nombres indiquent des zones des activités différentes,
voir chapitre de résultat)

the source area of the rock fall material. The rooting zone and tongue zone are covered by a coarse grained layer which contains blocks with a size of several meters. The steep rock glacier front slope (40 – 50° slope angle) is well defined (Fig. 2) at an altitude of about 2.400 m a.s.l.. Big boulders at the toe of the talus slope indicate rock fall activity.

The deformation at the survey point 106 led to a repeated geologic survey of the rock glacier that originally was expected to be inactive. Instead of expanding the geodetic monitoring network, it was decided to intensify the remote sensing campaign with the aim to get spatial information about rock glacier deformation and to investigate the past deformation behaviour.

3. DATA

The rock glacier behaviour is reconstructed by means of already available data from national aerial imagery (1971, 1997, 2003, and 2009) and an ALS survey campaign (2006). From 2014 onward, we started the monitoring of the rock glacier by TLS.

3.1. Imagery data

The region was captured several times by national and federal aerial imagery campaigns. For the years 1971, 1997, 2003 and 2009 ortho-image maps of the study area are available. Ortho-images are images that are rectified from the central perspective to the ortho-projection. This geometric correction of the image distortion allows metric scale measurements on images.

3.2. TLS and ALS 3D point cloud data

The region is covered by a federal ALS flight campaign which provides a point cloud with a density of 1 – 4 points/m^2. Since 2014, additional high resolution point clouds were acquired by annual TLS field campaigns. The TLS data is recorded with a Riegl VZ 4000 long-range scanner (Fig. 2). The scanner is portable and can be used at areas which are only accessible by foot. Five scan positions (Fig. 1) are necessary to cover the entire rock glacier area from different directions. The distances between scanner positions and scanned slopes range from 300 to 1.800 m. In contrast to the ALS point cloud, the TLS point cloud has a higher point density with about 25 - 400 points/m^2. The TLS data from the individual scan positions had to be transformed from their internal scanner coordinate system into one common externally defined coordinate system (registration,

[8], [9]) and then into a global coordinate system with known geodetic datum (geo-referencing, [9]). Both, the registration and the geo-referencing, is done by matching the TLS point clouds onto an already geo-referenced reference point cloud by use of an ICP algorithm [10]. For the geo-referencing of the first TLS point cloud from 2014, the ALS point cloud was used as reference point cloud. The successive TLS scans were then matched onto the geo-referenced TLS point cloud from 2014. For registration and geo-referencing only unchanged areas were used. Geomorphological active areas, e.g. the rock glacier, were excluded from the point cloud matching. The ICP based registration has the advantage that a direct access into the deformation area in order to install targets is not necessary and that the data acquisition process is accelerated when the installation and scanning of targets is not required.

4. METHODS

The remote sensing data is analysed with the aim to extract information about surface changes like displacements, mass gain and mass losses, rockfall scarps and deposits as well as debris relocation. Processes with a destruction of the surface structure (e.g. rockfall, debris relocation) are analysed by measuring the distance between the pre-failure and the post-failure surface. Processes, which result in terrain displacements (e.g. en-block slides) are analysed by measuring the displacement of homologous parts found in two data sets.

4.1. Displacement analysis

Slope displacements (i.e. the en-block movement of parts of a slope) are analysed with image correlation techniques [11]. The principle of image correlation is based on the detection of corresponding features by searching patterns with a similar texture in two images from different epochs. A prerequisite for image correlation techniques is the preservation of the surface texture in both images. If the surface texture is destroyed (e.g. by rockfall) or has a low contrast (shadowed areas in ortho-images), no corresponding features can be found and no or only miscorrelations occur. Miscorrelations can be identified by analysing the surface texture in both images and the corresponding displacement vector patterns. Vectors from miscorrelations scatter in all directions within the search window and the vector lengths vary strongly.

Image correlation based on ortho-images provides information about the horizontal displacement, including length and direction. Image correlation based on elevation data, like Digital Elevation Models (DEM) derived from laser scanning, adds the vertical component and thus makes it possible to derive real displacements (xyz) and information about the length, direction and dip of the displacement.

Instead of using point clouds directly, these are triangulated to a raster DEM and then processed to a shaded relief image before the analysis.

The accuracy of the image correlation results depends on the quality of the input data. Registration errors or geometric errors from photogrammetric processing have to been quantified in order to avoid a confusion of data uncertainties and real displacements. This is done by the definition of a distance threshold, which allows to distinguish between real displacements and data uncertainties (Level of Detection – LoD). In this study, the LoD of the image correlation analyses is determined by considering the second standard deviation of the displacement vector length in geological and geomorphological stable areas.

4.2. Distance change analysis

Distance change analysis is used to identify processes i) in areas where the surface structure has been altered (e.g. rockfall, debris slides) and ii) in areas with mass loss and mass gain (e.g. ice and snow melt, scarp and deposit areas). Here, we apply a 3D distance measurement approach [12], which was developed especially for rough alpine slopes and is robust against data noise and data gaps. The distance between the surfaces of two epochs is measured along the direction of the normal of a tangent plane fitted to the surface, and thus not necessarily in the vertical direction. The approach, based on point cloud data, has the advantage to preserve the available 3D information. In contrast to raster DEM based differencing, the approach is applicable even to overhanging areas and very steep terrain. In this study the LoD of distance change measurements is estimated with a confidence interval of 95%, considering spatially variable uncertainties caused by positional errors, surface roughness, and the registration error [12]. If the measured distance is larger than the LoD, it is considered as real change.

5. RESULTS

The results of the image correlation analyses (Fig. 3 and Fig. 4) as well as the distance measurement analysis (Fig. 5) show the activity of the rock glacier. Fig. 3 and Fig. 4 depict the annual velocity, calculated by dividing the absolute displacement length by the number of years of the period under consideration. It is assumed that the real displacement rates have varied within each period. As we do not have continuous measurements of the rock glacier displacement, this does not show up in our analysis. Historic ortho-image based image correlation analyses (Fig. 3) show the displacement of the rock glacier tongue towards North West. At the rock glacier rooting zone no displacements are displayed. This is because i) on the historic ortho-images large parts of the rooting zone are in the shadow of the steep north facing walls and no correlations can be found and ii) the displacements are smaller than the LoD (Table 1).

Table 1
LoD of displacement analysis for each dataset pair,
total displacement and velocity [m/a] at control points
LoD de l'analyse de déformation pour chaque couple des données,
Déformation total et la vélocité [m/a] aux points contrôlés

EPOCH	SOURCE	NO. YEARS	LOD [M]	DISPLACEMENT [M] AT CONTROL POINT			VELOCITY [M/A] AT CONTROL POINT		
				P1	P2	P3	P1	P2	P3
1970 - 1997	Ortho-image	27	1.20	4.32	7.29	3.78	0.16	0.27	0.14
1997 - 2003	Ortho-image	6	1.30	2.64	3.48	-	0.44	0.58	-
2003 - 2009	Ortho-image	6	0.90	3.84	5.22	1.5	0.64	0.87	0.25
2006 - 2014	ALS - TLS	8	0.45	6.32	7.04	1.84	0.79	0.88	0.23
2014 - 2015	TLS	1	0.15	1.29	1.2	0.48	1.29	1.20	0.48
2015 - 2016	TLS	1	0.05	1.42	1.37	0.43	1.42	1.37	0.43

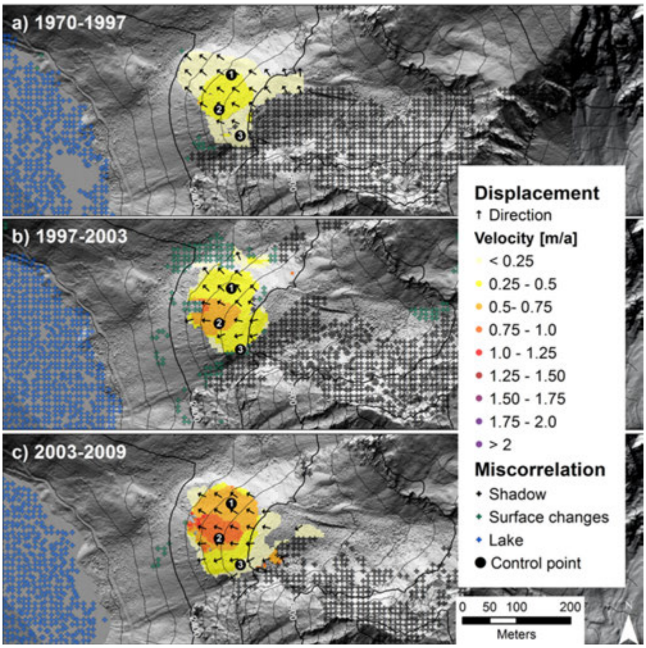

Fig. 3
Displacement analyses based on historic ortho-image data
Analyse de déformation á base d'ortho photographies historiques

In contrast to the ortho-image based displacement analyses, displacement analyses based on laser scan data (Fig. 4) have a better coverage because laser scanning as an active remote sensing technique is not affected by sun shadows. Furthermore, smaller LoDs can be achieved. Since the first TLS campaign from 2014, the scan settings were improved from year to year and a smaller LoD and a better coverage are achieved. The laser scan data shows rock glacier displacements of the rooting zone towards West. The velocity of the rock glacier is slow (< 0.5 m/a) in the rooting zone and is highest at the front parts of the rock glacier. The velocity of the rock glacier tongue steadily increased since 1971. Fig. 6 shows the displacements at different control points on the rock glacier. The artificial control points (P1 - P3) were introduced to inspect the displacement at these locations (see Fig. 3 and Fig. 4). The velocities [m/a] are shown in Table 1. In the period 1970-1997 the maximum velocity of the rock glacier tongue was about 0.3 m/a. In the following epochs, the rock glacier tongue accelerated to velocities higher than 1.4 m/a, as measured in 2015 and 2016.

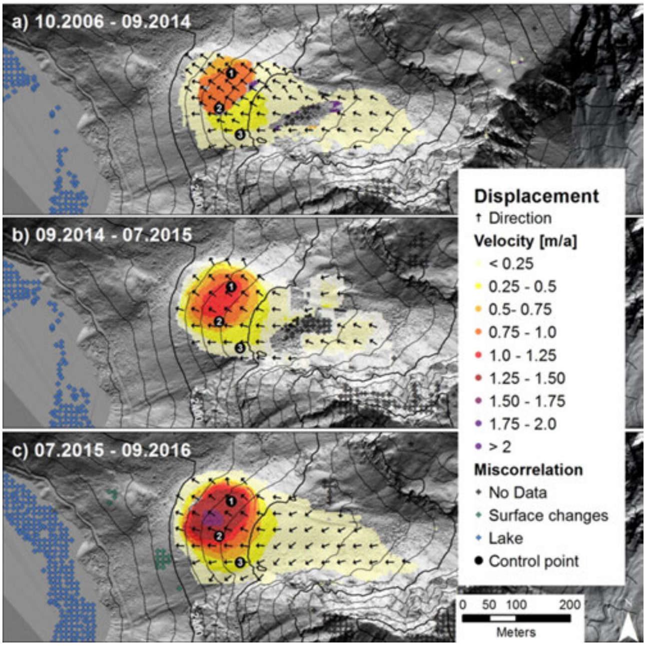

Fig. 4
Displacement analyses based on laser scan data
Analyse de déformation à base de laser scan

The distance change analysis of the epoch 2006/2016 (Fig. 5) provides additional support for a classification of the rock glacier into different subareas. At the rooting zone (subarea i), positive and negative distance changes are alternating, which can be attributed to a steady but slow displacement of the rooting zone. West of the ridge, which divides the rooting zone from the active rock glacier tongue, an area with negative distance changes (subarea ii) indicates mass losses. Adjacent to that depletion area, an area with positive distance changes indicates mass gain (subarea iii). The north-western part of the rock glacier tongue (subarea iv) and its front slope (subarea v) show no significant distance changes and displacements. The distance change analyses show further surface changes due to debris and block relocation on the talus slope (subarea vi) as well as snow fields.

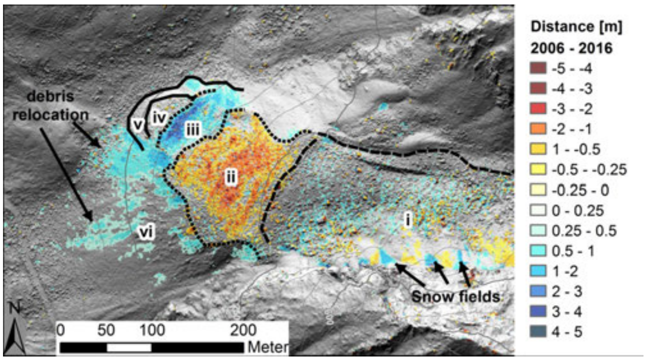

Fig. 5
Distance change analysis of the lasercan data 2006 - 2016 with i) root zone, ii) active lobe with iii) front slope, iv) inactive/ less active lobe with v) front slope and (vi) talus slope with rockfall and relocated debris
Analyse de changement de distance a bases de données laser scan 2006 – 2016 avec différentes zones d'activité

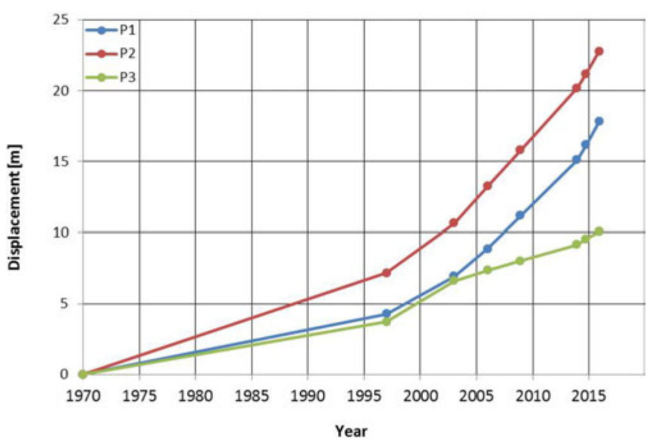

Fig. 6
Accumulated displacement from 1971 to 2016 at control points P1, P2 and P3
Déformation à l'époque de 1971 à 2016 aux points P1, P2 et P3

6. DISCUSSION

An acceleration of rock glacier movement since the beginning of the 21th century, like observed at the Finstertal rock glacier, is also reported for many rock glaciers in the European Alps [13], [14], [15], [16], [17]. These recent accelerations are a direct response to increasing mean annual temperatures. The warmer air temperatures are causing an increase of permafrost temperatures and a change of the ice-mechanical properties [18]. Rock glaciers with ground temperatures close to 0° slide faster than colder ones [14].

The spatial variations of the movements, especially the differences between the rooting and the tongue zone, are observed also at other rock glaciers [15]. The spatial speed variations between the rooting and the tongue zone, which are separated by an ogive-like transverse ridge, depend on the topography. The opening of the cirque allows a horizontal extension which is expressed in higher velocities at the tongue zone. The spatial variations at the tongue zone are caused by different deformation behaviour of the two lobes (Fig. 5). The more active lobe (subareas ii and iii) overrides the less active or inactive front lobe (subarea iv and v). The fast movement of the active lobe causes an extension, which results together with ice melt in negative surface elevation changes in subarea ii. On the front slope (subarea iii) of the active lobe, the advance causes the accumulation of debris and blocks. The high activity of the lobe also results in rock fall and debris relocation on its lateral border, with material accumulation on the talus slope (subarea vi). The increasing speed of the rock glacier causes an imbalance between mass transport at the tongue area and debris and boulder supply at the rooting zone. This imbalance will most probably lead to an inactivation of the rock glacier in the future [14].

The geodetic measurements of the target point 106, located at West-South-West orientated talus slope on the left side of the rock glaciers active lobe, show displacements of about 0.005 m per year. For all multi-temporal data sets, the LoD of the presented deformation measurement methods is greater than 0.005m. Consequently, the displacements at the location of survey point 106 are not shown in the analyses of multi-temporal ortho-images, ALS or TLS data. Geodetic monitoring allows sub centimetre precisions but only single point measurements. Photogrammetric or laser scanning data in rough alpine terrain will hardly achieve sub centimetre precision [12]. In the case of the rock glacier Finstertal, photogrammetric or laser scanning data are better suited for the understanding of the kinematics of the rock glacier than single point information. The spatial information allows the detection of zones with different activities and different processes since 1971. Rock glacier monitoring based on an enhanced geodetic network cannot be used to reconstruct past slope deformations and is furthermore more time and labour intense. The choice of characteristic spots for the installation of geodetic survey points is less efficient without a-priori knowledge of displacement fields. Survey points on boulders on the rock glacier may be influenced by block rotation and may not represent the kinematic of the entire system. The explanation of the rock glacier kinematic by means of single point measurements would require a high number of target points. Consequently, the monitoring of the rock glacier will be continued by TLS.

In summary the rock glacier is highly active at present and is more active than it was the three decades before.The spatial information from remote sensing data of the Finstertal rock glacier shows that the main flow direction of the tongue zone is towards North-West.The tongue zone ends in a flat depression of the slope and is not affecting the reservoir. The rock glacier is source of fragmented rock and boulder fall and, in case of heavy rain, debris flows.These processes have no relevant impact on the reservoir because the slope flattens out above the shore line at full supply level and the volume of rockfall and debris slides is too small.

The methods for retrospective deformation monitoring and ongoing monitoring presented in this study are applicable to other study sites and processes (e.g. rockfall, landslides, [19]). The success of the historic ortho-image correlation depends on the quality and coverage of the ortho-image scene. Steep and shadowed or vegetated areas are not suited for image correlation.

In this study, we used TLS measurements for deformation monitoring. UAV based photogrammetric point clouds would yield quite similar results. In contrast to TLS monitoring, a UAV based monitoring requires the identification of ground control points well distributed over the area. The installation and measurement of ground control points is time consuming, labour intense and restricted to save areas, which are not endangered by rockfall. TLS monitoring with an ICP based registration approach is also suited for the monitoring of dangerous slope parts (e.g. rockfalls) because direct access into the study area is not necessary. Furthermore, at study sites with higher vegetation, laser scanning is better suited than photogrammetry as the detection of multiple returns from each laser pulse makes it possible to filter out the vegetation.

7. CONCLUSION

The spatial information obtained from remote sensing based monitoring make it possible to identify the spatially variable deformation behaviour of the Finstertal rock glacier.The analyses of historic ortho-images enable the reconstruction of past deformations. The combination of TLS data with already acquired ALS data provides deformation results directly after completion of the first TLS field campaign. Remote sensing based monitoring techniques will supplement and not replace geodetic measurements. A supplementation of geodetic measurements (e.g. early warning systems using total stations) with remote sensing techniques used for the interpretation of deformation processes, enables a holistic deformation monitoring network. The spatial 3D documentation of reservoir slopes by laser scanning is of great interest in the case that sudden and unexpected slope deformations have to be analysed.

REFERENCES

[1] VOSSELMAN, G., MAAS, H.-G. (Hrsg.): Airborne and terrestrial laser scanning. Dunbeath: Whittles Publishing, 2010.

[2] ABELLÁN, A., OPPIKOFER, T., JABOYEDOFF, M., ROSSER, N. J., LIM, M., LATO, M. J.: Terrestrial laser scanning of rock slope instabilities. Earth Surface Processes and Landforms 39 (2014), H. 1, S. 80–97.

[3] DALL'ASTA, E., FORLANI, G., RONCELLA, R., SANTISE, M., DIOTRI, F., DI MORRA CELLA, U.: Unmanned Aerial Systems and DSM matching for rock glacier monitoring. ISPRS Journal of Photogrammetry and Remote Sensing 127 (2017), S. 102–114.

[4] PEPPA, M. V., MILLS, J. P., MOORE, P., MILLER, P. E., CHAMBERS, J. E.: Brief Communication: 3D landslide motion from cross correlation of UAV-derived morphological attributes. Natural Hazards and Earth System Sciences Discussions (2017), S. 1–13.

[5] SCAIONI, M., LONGONI, L., MELILLO, V., PAPINI, M.: Remote Sensing for Landslide Investigations: An Overview of Recent Achievements and Perspectives. Remote Sensing 6 (2014), H. 10, S. 9600–9652.

[6] BARSCH, D.: Rockglaciers: Indicators for the Present and Former Geoecology in High Mountain Environments. Berlin, Heidelberg: Springer Berlin Heidelberg, 1996.

[7] KRAINER, K., BRESSAN, D., DIETRE, B., HAAS, J. N., HAJDAS, I., LANG, K., MAIR, V., NICKUS, U., REIDL, D., THIES, H., TONIDANDEL, D.: A 10,300-year-old permafrost core from the active rock glacier Lazaun, southern Ötztal Alps (South Tyrol, northern Italy). Quaternary Research 83 (2015), H. 02, S. 324–335.

[8] CLAGUE, J. J., STEAD, D. (Hrsg.): Landslides. Cambridge: Cambridge University Press, 2012.

[9] HUNGR, O., LEROUEIL, S., PICARELLI, L.: The Varnes classification of landslide types, an update. Landslides 11 (2014), H. 2, S. 167–194.

[10] HUGGEL, C., KHABAROV, N., KORUP, O., OBERSTEINER, M.: Physical impacts of climate change on landslide occurrence and related adaptation.

In: Clague, J. J., Stead, D. (Hrsg.): Landslides. Cambridge: Cambridge University Press, 2012, S. 121–133.

[11] FEY, C., RUTZINGER, M., WICHMANN, V., PRAGER, C., BREMER, M., ZANGERL, C.: Deriving 3D displacement vectors from multi-temporal airborne laser scanning data for landslide activity analyses. GIScience & Remote Sensing 52 (2015), H. 4, S. 437–461.

[12] FEY, C., WICHMANN, V.: Long-range terrestrial laser scanning for geomorphological change detection in alpine terrain - handling uncertainties. Earth Surface Processes and Landforms (2017), H. 42, S. 789–802.

[13] KRAINER, K., HE, X.: Flow velocities of active rock glaciers in the Austrian Alps. Geografiska Annaler, Series A: Physical Geography 88 (2006), H. 4, S. 267–280.

[14] KÄÄB, A., FRAUENFELDER, R., ROER, I.: On the response of rockglacier creep to surface temperature increase. Global and Planetary Change 56 (2007), 1-2, S. 172–187.

[15] GÄRTNER-ROER, I., LAMBIEL, C., DELALOYE, R., 2010: Overview of rock glacier kinematics research in the Swiss Alps: seasonal rhythm, interannual variations and trends over several decades.

[16] KELLERER-PIRKLBAUER, A., KAUFMANN, V.: About the relationship between rock glacier velocity and climate parameters in central Austria. Austrian Journal of Earth Sciences (2012), 105/2, S. 94–112.

[17] SCOTTI, R., CROSTA, G. B., VILLA, A.: Destabilisation of Creeping Permafrost: The Plator Rock Glacier Case Study (Central Italian Alps). Permafrost and Periglacial Processes 28 (2017), H. 1, S. 224–236.

[18] KRAUTBLATTER, M., FUNK, D., GÜNZEL, F. K.: Why permafrost rocks become unstable: a rock–ice-mechanical model in time and space. Earth Surface Processes and Landforms 38 (2013), H. 8, S. 876–887.

[19] FEY, C., WICHMANN, V., ZANGERL, C.: Reconstructing the evolution of a deep seated rockslide (Marzell) and its response to glacial retreat based on historic and remote sensing data. Geomorphology 298 (2017), S. 72–85.