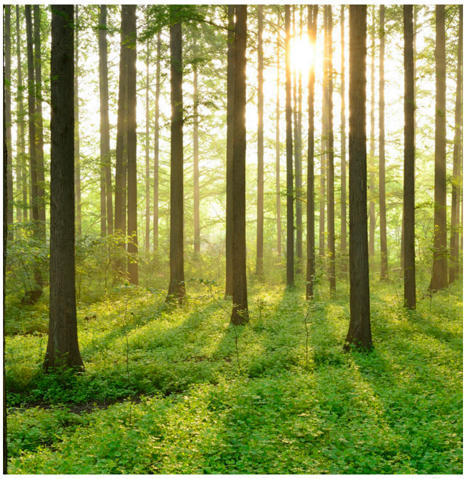
INSAR ON EMBANKMENT DAMS

REPORT 2015:212

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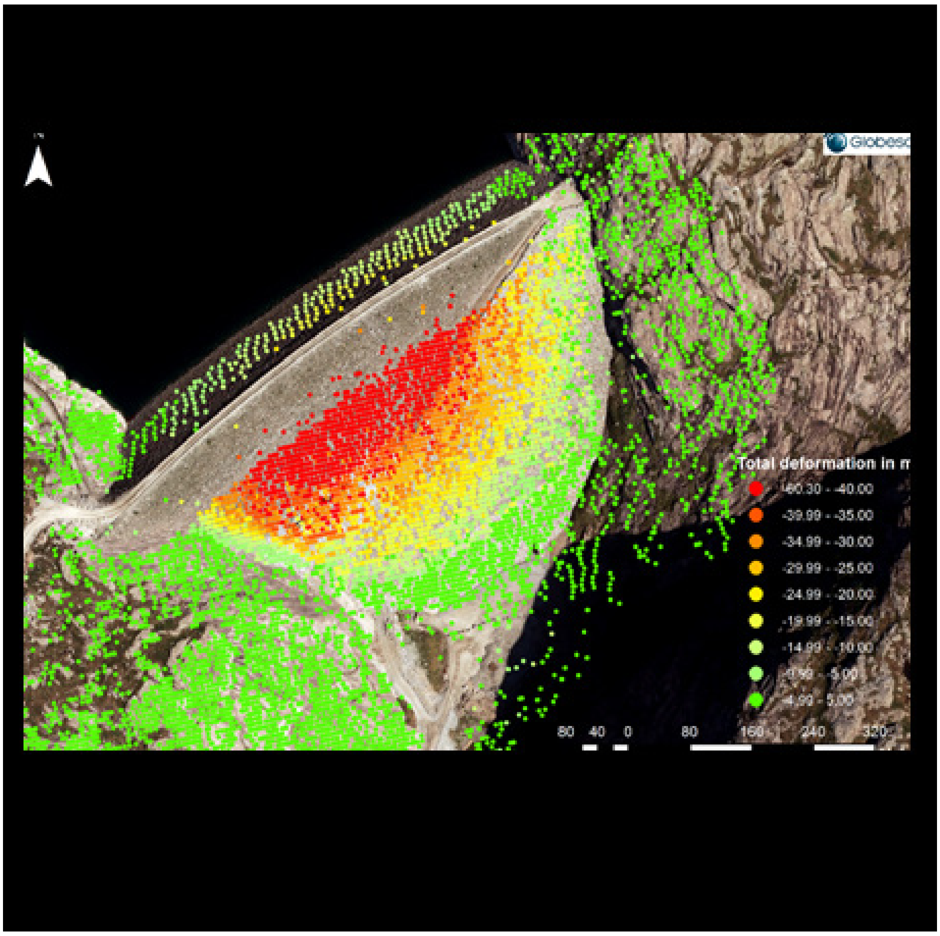

Energiforsk

InSAR on Embankment dams

Pilot on deformation measurement

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Foreword

In this study the potential of Interferometric Synthetic Aperture Radar (InSAR) to provide timely settlement measurements in high spatial resolution has been tested on four dams in Norway and Sweden.

The results show that InSAR provides data that is consistent with the settlement patterns expected and with the manual geodetic ground measurements for the dams of Akersvatn and Ajaure. The study shows that the InSAR methodology can give reliable settlement data with little variation and high temporal and spatial resolution for dams.

The report has been written by Øyvind Espeseth Lier, Frano Cetinic, Ingvar Ekström, Tom Rune Lauknes, Yngvar Larsen. The conclusions in the report are the authors and does not necessarily represent the view of Energiforsk or the participants in Energiforsks dam safety development program.

The project has been a part of Energiforsks dam safety R&D program with participation from hydro power companies and Svenska kraftnät.

Stockholm November 2015

Cristian Andersson

Authors acknowledgements

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Sammanfattning

Under de senaste åren har det skett en omfattande förbättring i precisionen för olika former av fjärranalys, både avseende mark-, och satellitbaserade mätmetoder. En av dessa metoder, som genomgått en snabb utveckling i positionsbestämning och mätning av relativ rörelse av objekt på marken, är InSAR (Interferometric Synthetic Aperture Radar), en form av satellitbaserad mätteknik. Tillgång till nya satelliter och förbättrade analysmetoder har gjort denna mätmetod intressant för kraftindustrin.Att den ger yttäckande övervakning av deformation och krypning i dammkonstruktioner och kringliggande mark gör den också intressant.

Under senare år har flera studier genomförts som visar på potentialen i denna mättekniks förmåga att bidra till dammsäkerheten genom att leverera mätdata med hög rumslig upplösning. För att undersöka mätmetodens noggrannhet under olika förhållanden har en studie genomförts av fyra kraftverksdammar i Sverige och Norge under 2013 – 2014. De fyra dammarna, Akersvatn, Ajaure, Rieppejavri och Svartevann, har valts ut då de representerar olika utmaningar för InSAR-tekniken genom dammarnas storlek, utformning, orientering, topografiska förhållanden och varierande klimatologiska förhållanden. Parallellt med InSAR-mätningarna har traditionella geodetiska mätningar utförts vid tre av dammarna för att erhålla referensdata för verifiering av satellitmätningarna.

Från de geodetiska mätningarna i Ajaure och Akersvatn erhölls data som var tillräckligt noggranna för att en detaljerad avstämning skulle kunna göras mot mätresultaten från InSAR. Den visar för dessa dammar att det deformationsmönster som uppmättes i InSAR har en god överensstämmelse med de manuella referensmätningarna och visar även rimliga resultat avseende naturliga årliga variationer, utifrån temperaturpåverkan och magasinsvariation.

Resultatet från studien visar på en god tillförlitlighet i mätmetoden, med små avvikelser från de användbara geodektiska mätningarna och en hög upplösning. Utifrån resultaten bedöms InSAR vara väl lämpad för deformationsövervakning, speciellt där säsongsberoende variationer förekommer, som kräver täta geodetiska mätningar för att erhålla förståelse för dammens rörelsemönster, eller där stora ytor, eller svåråtkomliga områden, behöver övervakas.

Summary

In recent years, remote sensing has been applied to dam surveillance, specifically the technique of Interferometric Synthetic Aperture Radar (InSAR), where ground movements can be monitored with high precision. The potential for this technology to enhance dam safety by providing timely settlement measurements in high spatial resolution has been demonstrated in several studies. For dam safety applications, the reliability and consistency will have to be tested prior to InSAR being broadly adopted among more traditional trusted and conventional methods.

To this purpose, four rock fill dams in Norway and Sweden have been monitored 2013-2014. The rock fill dams; Akersvatn, Ajaure, Rieppejavri and Svartevann are of different sizes, design, orientation and are located in different climatological conditions that each represents different challenges to the InSAR technique. Parallel to the remote sensing, traditional geodetic measurements were performed at three of the dams according to established procedures to compare the methodologies and to prove the accuracy of the InSAR deformation monitoring. The results for the dams of Akersvatn and Ajaure show that InSAR provides data that is consistent with the manual geodetic ground validation and the settlement patterns expected. The InSAR methodology also has been proven to give reliable, consistent settlement data with little variation and high resolution – proving that the method is very suitable for monitoring purposes.

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1 Introduction

The hydropower dam boom of the 1950–60s has led to an ever-increasing population of dams that are now approaching their planned design life. Due to problems related to aging, remoteness of many dam sites and a legacy of market deregulation, dam owners and authorities are becoming increasingly aware of necessary risk management and its accompanying costs. The risk and consequence level that society accepts has notably changed since the construction of these dams, which in many cases requires the dam owner to either let their facility undergo an extensive construction upgrade, or conduct a comprehensive upgrade of the instrumentation and monitoring program. As a manifestation of this, there are increasing demands for cost effective monitoring of dam behavior.

All monitoring equipment, be it traditional geodetic monitoring or newer methodology using temperature gradients, microwave scanners, or advanced stress/strain cells transplanted into a dam body, need to be calibrated, be of high quality and be well understood, for the results to be useful for dam safety work. The output data must be trustworthy and possible to verify. The reason for this becomes apparent when instrumentation indicates abnormal dam behavior. Data from instruments can then be correlated to dam safety risks with possible impact on human lives, property and lost production – all of which have economic and legal impact on the dam owner. Appropriate mitigation measures will be based on the understanding of the problem originating from the data recorded by the instrumentation.

The basic methodological approach to instrumenting a dam has remained largely unchanged by technological advances. Instruments and methods have evolved, but they are still relating to monitoring the same physical mechanisms. For rock- and earth fill dams these can be grouped into four main groups of instruments;

1. Leakage
2. Deformations
3. Pore pressure
4. Water levels

Depending on the consequences of dam failure, several different instruments can be installed to ensure that all failure modes are captured, as well as intra-dependent verification of readings. The challenge is to find cost effective measures to cover all relevant failure modes.

This project has focused on settlement measurements of rockfill dams, which there has been a renewed interest in due to increased understanding of dam behavior throughout its design life. The old instrumentation philosophy was usually that settlement measurements served only to verify the design, whereupon the monitoring equipment often were gradually phased out and lost importance. After decades of operation, the understanding of failure modes has evolved so that currently the understanding is that the best practice is to continue monitoring throughout the dams life. It is clear that surface settlement monitoring has an important role in the understanding of a number of important failure modes that do not manifest themselves in regard of changes in leakage or pore pressure. This in particular in regard of modern high dams that are currently pushing the design limits of several dam types. This for example concerns

Concrete Faced Rockfill Dams (CFRD) that are currently constructed record high in China and Brazil, demanding changes and adaptations in previously accepted design criteria and understanding of material behavior during extreme load conditions.

The current most common practice of measuring only a sparse amount of bolts on the dam slopes, as well as bolts in the dam core, can be criticized for not capturing events in a dam on a larger scale, unless the bolts are mounted with a very high density over the dam body. The displacement analysis of the settlement data has also been a challenge to process and interpret, often with a notably difficulty in accuracy and in northern countries also in combination with disturbing background noise from for example ground frost affecting the bolts. This has resulted in deformation monitoring often being downgraded in importance, as it often provides imprecise and contradictive data that requires long-term commitment to verify.

Satellite radar interferometry (InSAR) has in recent years become ever more accurate and cost effective with the arrival of commercial high-resolution SAR satellites and ever decreasing processing costs. In Scandinavia, the hydropower industry has pioneered the use of InSAR in dam safety and demonstrated the technical capacity and potential of the technology. The objective with introducing InSAR in the hydropower industry is to radically improve the possibilities of reliable and precise surface deformation monitoring, which will allow this type of instrumentation to serve a central purpose in the dam safety methodology of today. In order to establish the method as an industry standard, by verifying the accuracy of InSAR and build experience, the dam industry organizations in Norway and Sweden joined forces with utilities and the Norwegian Space Centre, to run a two-year development effort, which has culminated in this study.

The goals of the project were to:

1. Demonstrate technical opportunities and limitations the application of InSAR has on mapping deformation of rockfill dams.
2. Define the added value provided by InSAR to dam safety and operations
3. Communicate and spread knowledge of the InSAR technology to the industry, authorities and relevant industrial bodies.

2 Methodology

2.1 TRADITIONAL GEODETIC MEASUREMENT

The traditional method for measurements of deformation and subsidence at embankment dams is to measure movements in bolts that have been inserted into drilled holes in the dam body. The bolts are divided into three groups that give different information when measured:

- Core bolts – to monitor subsidence in the impervious core
- Crest bolts – to monitor subsidence and displacement in the dam crest
- Deformation bolts - to monitor subsidence and displacement in the slope.

Figure 1 shows a sketch of the common distribution of the bolts for an embankment dam.

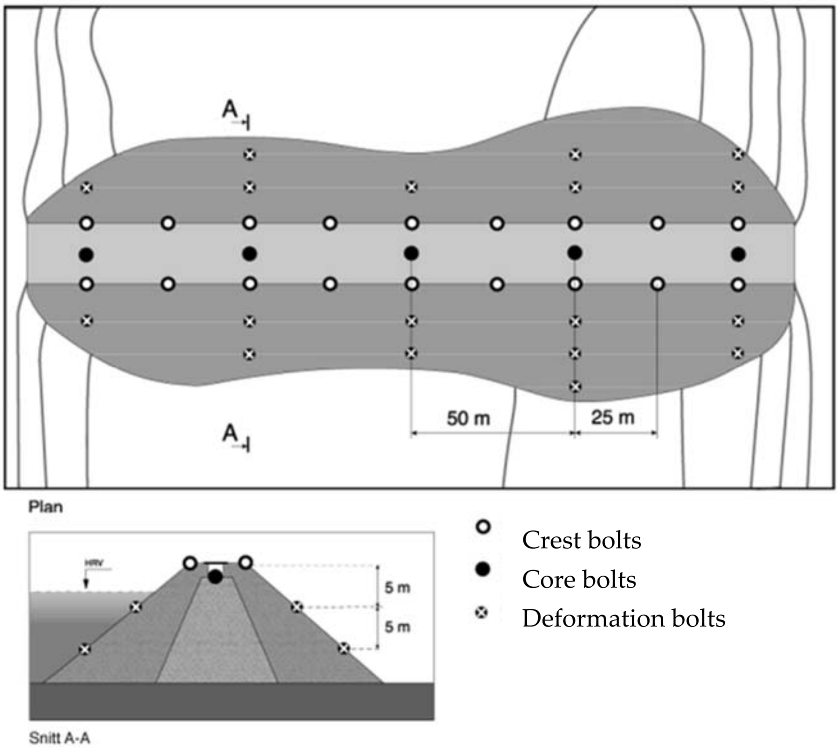


Figure 1. Distribution of bolts for an embankment dam seen from above and from the side. Source: NVE's code of practice for the monitoring and instrumentation of water infrastructure, Second edition, October 2005.

The frequency of measurement of the bolts depends on the needs. The dam consequence class and dam type determine the frequency, according to the code of practice for the monitoring and instrumentation of water-course structures published by NVE in Norway and Swedenergy in Sweden. Unless the dam is under construction or refurbishment, the bolts are to be measured and audited at each principal inspection, i.e. every five years for dams in safety classes 2-4 in Norway, in Sweden annually for dams belonging to the highest two consequence classes. Practices differ around the world, and the frequency is often determined by an inspection programme to which other instruments also contribute.

2.1.1 Challenges when measuring crest and deformation bolts

Several problems associated with the measurement of existing crest and deformation bolts have been identified in dialogue with dam owners and consultants in the energy-supply industry. These problems can be classified under three headings:

1. Existing measurement methods do not provide information about deformations between the bolts. The monitoring bolt thus covers but a fraction of the dam surface.

2. The method has many sources of reading and processing errors, which sometimes might be discovered first after a considerable time has passed and it is not possible to go back and verify the reading. In some cases the data will be unfit for use even after an effort has been made to rectify errors, resulting in gaps in the measurement data.

3. Existing measurement programmes are typically limited to the dam. This means that displacement in the surrounding terrain (such as rock slopes above the dam and the reservoir) are seldom detected unless the magnitude of deformation is high.

Measurement of bolts gives a single value at each point. The limitation on the practical number of bolts on the dam surface gives a very coarse image of movements of the dam surface. Bolts embedded in the body of the dam can move as a result of many causes, not only natural processes, but also unforeseen events, where snow and ice, people, animals, vehicles or freeze/thaw processes move the measurement bolts. It is not unusual that one or several bolts in a network are affected. It is difficult or impossible in many cases to determine whether deformation of bolts is a result of real movement, measurement error, or actual but unforeseen movement of the bolts.

Most dams have been built using local height systems. The transition to national reference systems and map projections has caused problems in several measurement series, and often this may not be discovered until data that cover a long period of time have been analysed and presented. In the worst case, the complete measurement series may be unusable.

Measurement of the bolts is usually limited to the body of the dam, and there may be dangers that cannot be discovered with existing measurement methods. The construction of dams and reservoirs is a human intervention that changes the natural drainage conditions around the reservoir. Changes in water level can contribute to erosion of slopes in the reservoirs and pore pressure build-up, which can cause landslides. The soil masses released in a landslide may form flood waves that can damage the dam and, in the worst case, lead to dam failure.

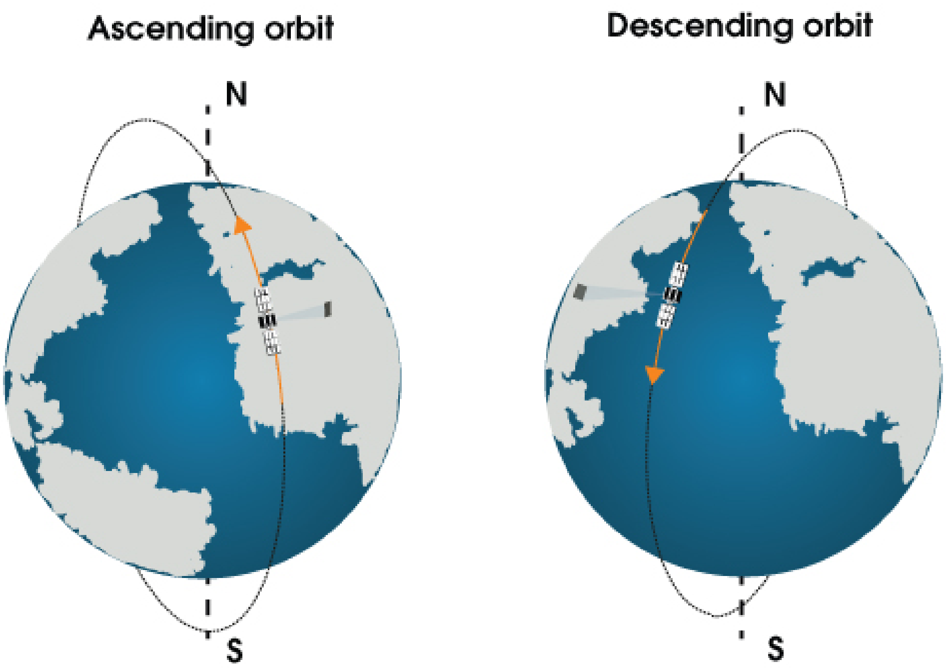
Core bolts measure movements of the dam core and deformations inside the dam, and are therefore not directly relevant to this experiment.

2.2 INSAR DATA COLLECTION

2.2.1 Data acquisition

Synthetic Aperture Radar (SAR) is an instrument commonly installed in polar orbiting, earth observation satellites, as it has proven insensitive to light and meteorological conditions. The radar is side looking, which lends importance to which direction the satellite is orbiting.

Satellites that are equipped with SAR instruments move continuously in near-polar orbits, between 500 and 800 km above the ground. The rotation of the Earth and the continuous movement of the satellite create two different measurement geometries: one arises when the satellite passes from south to north (the ascending orbit), and the other arises when the satellite passes from north to south (the descending orbit), Figur 2.



Figur 2 Measurement geometry of ascending (left) and descending orbit (right).

In a descending orbit, the radar measurements have highest sensitivity in areas that face to the west, while in an ascending orbit the radar measurements cover areas that face to the east. The satellite SAR imaging geometry thus limits the applicability to perform surface displacement analysis. Further, the radar is only sensitive to displacement that has a component in the radar line-of-sight (LOS) direction. Sensitivity is thus limited in cases where the actual surface displacement vector is near perpendicular to the LOS. Earth observing satellites in polar orbits fly in a direction close to North-South direction, thusthe sensitivity to north-south displacement in the horizontal plane is low. By combining SAR measurements from both ascending and descending geometries vertical and east-west movement components can be extracted.

2.2.2 Data analysis

Repeat-pass synthetic aperture radar interferometry (InSAR) makes use of the SAR satellite data and has over the last decades proved itself as an extremely powerful tool for measuring terrain displacement (Massonnet and Feigl, 1998; Rosen et al. 2000). SAR interferometry is based on a coherent combination of two (or more) complex valued SAR images.

The technology examines the phase shift between two radar measurements. Each radar measurement (electromagnetic wave) has a wavelength, which is the distance between the peaks of the waves, **Fel! Hittar inte referenskälla.**. The phase contains information about the position of the wave in its sinusoidal cycle. The wave may be at the top, the bottom or at another intermediate position, and a radar system can measure the phase of each wave that is reflected back to the radar.

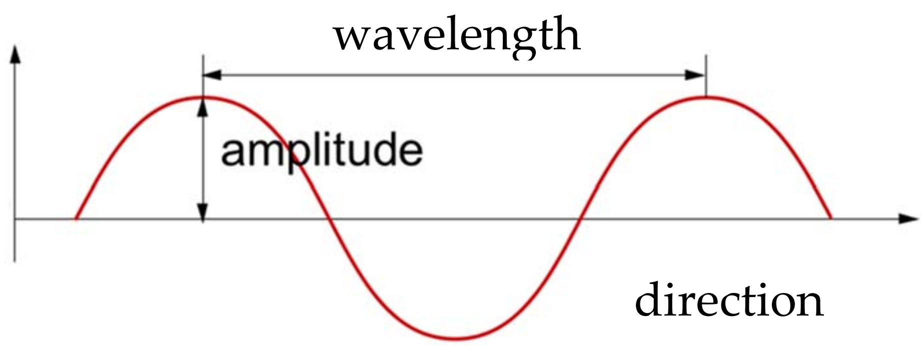


Figure 3. The wavelength is the distance between two peaks of an electromagnetic wave.

If a point on the ground has not moved since the previous reading, the subsequent radar wave will, in principle, move the same distance, and no phase shift will in this case take place. In situations in which a point on the ground has moved away from or towards the radar, the subsequent radar waves will arrive back at the radar with a shifted phase. The phase shift that results has therefore been caused by the movement of the reflecting point on the ground, **Fel! Hittar inte referenskälla.**.

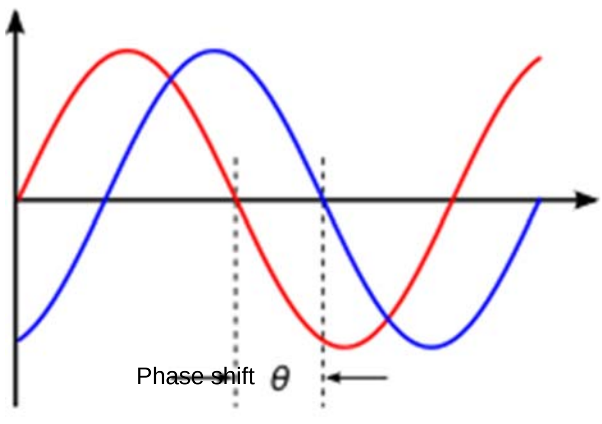


Figure 4. The change in phase between two radar waves is known as the "phase shift".

The observed phase difference between the two SAR images, captured at different times, is called the interferometric phase, and is the sum of several signal components: topography, terrain deformation in the radar LOS between the acquisitions, and atmospheric differences. The phase difference between two SAR images can then be used to detect millimeter to centimeter scale ground deformation patterns.

In practice, several radar measurements, taken with the same satellite geometry, are combined using advanced time-series InSAR processing methods. Such methods are able to filter out various sources of error such as changes in the atmosphere and errors in the height model used. The final results are time series of deformations at the points where deformation data could be produced. Limitations are set essentially by vegetation, steep terrain (depending on the radar geometry), and snow.

The advanced time-series InSAR-methods developed during the first decade of this millennium can be divided into two categories, SBAS and PSI. SBAS-InSAR is most suitable for natural terrain and can produce InSAR measurements at most points/areas where the vegetation is not too dense. The spatial resolution of the final result is poorer than the resolution of the instrument since the SBAS measurement technique is based on calculating spatial statistics (the mean of a limited number of neighbouring pixels), and in this way calculating the deformation of an area. This is not, in practice, a limiting factor when high-resolution satellite sensors are used. In order to produce time-series of deformations using the SBAS-InSAR technique, approximately 12–15 radar satellite measurements (orbit passages) are required with the same geometry.

The other advanced InSAR technique is PSI-InSAR. This technique can deliver higher resolution of the InSAR measurements than SBAS-InSAR, and can, in theory, give one measured value for each per pixel in the radar image. The technique studies only the most stable signals that are reflected back to the satellite (known as "*persistent scatterers*"). These are typically large rocks, houses, buildings and human constructions. The SBAS method will often give better coverage when monitoring natural terrain since few persistent scatterers are present in such areas. The PSI technique will usually produce a more dense set of measurement points than SBAS when mapping infrastructure and rock-fill dams. In order to produce time-series of deformations using the PSI technique, at least 20-25 radar satellite measurements are required.

The choice of InSAR technology will be determined on the current situation, and is the result of the users' needs and technical requirements.

2.2.3 Availability of historical data

Radar satellites have been orbiting the earth since early 1990's and there are now large databases of available SAR data that can be utilized to study historical deformation trends. Various satellites have acquired data during different time-periods and at different locations, so one should always double check the availability of satellite data for the area of interest.

2.2.4 Challenges of applying InSAR

One general limitation of the InSAR technique is that accurate measurements cannot be made when the ground is snow-covered, since the contribution of the snow to the radar signals cannot be filtered out. Further, areas with dense vegetation give poor and noisy signals, making it difficult to produce deformation data in such areas, however . vegetation is seldom a problem at rock-fill dams.

Other limitations relate to radar geometry, such as radar shadow and layover. These are effects that are stronger in areas with steep and hilly topography, but they can present challenges also for dams. Limitation imposed by radar geometry can be avoided to a certain extent by carrying out measurements at several different geometries (directions) and with different angles of incidence for the remote sensing radar measurements.

2.3 SELECTION OF TEST POPULATION

For the project, four rockfill dams in Norway and Sweden were made available by the hydropower industry and selected for the study, as they have long-term documentation from manual geodetic monitoring that was to serve as background data for the validation process of the InSAR monitoring. This small population represents dams of different sizes (height and length), material composition of downstream face (large rock, gravel/soil), orientation of dam face, climatological conditions and surrounding topography. The selection had been made to represent as varying monitoring conditions as possible, to validate the potential influence on the InSAR read-out from different monitoring conditions.

Table 1 Salient features of the four rockfill dams studied.

	Ajaure	Akersvatn	Rieppejavri	Svartevann
Location	Norrland, Sweden	Nordland, Norway	Troms, Norway	Vest-Agder, Norway
Dam height	46 m	53 m	26 m	130 m
Length at crest	522 m	490 m	975 m	400 m
Regulating amplitude	9.5 m	43 m	41 m	81 m
Dam axis direction	West-Southwest	East	East-Southeast	South-Southwest
Storage capacity	5500 Mm^3	1276 Mm^3	145 Mm^3	1398 Mm^3
Year constructed	1964-66	1964-67	-1978	1973-1976
Last rehabilitation	2001-2002	2007-2009	n/a	2012-2014

These dams are instrumented with traditional bolts that are being measured geodetically, according to respective national regulations and guidelines.

Table 2 Existing settlement measurement instrumentation. Svartevann was rehabilitated 2012–2014 and will be instrumented 2015.

	Ajaure	Akersvatn	Rieppejavri
Dam downstream surface	43500 m^2	46000 m^2	48000 m^2
Number of bolts	29	99	101
Average area/bolt	1500 m^2	465 m^2	475 m^2
Measurements	Twice every year	Every five years	Every second year

2.4 VERIFICATION PROCESS

Measurements were made using the satellite TerraSAR-X, during snow free periods in 2013 and 2014. The satellite has different acquisition modes, meaning measurements can be made with different resolution and coverage. All dams were covered within the same satellite footprint since the dams cover a relatively small geographical area, in comparison to the satellite measurements. The resolution applied on each dam, varied between 1-3m per pixel. This in turn determined the measurement point density that could be produced, and that was further used during the verification process.

The traditional and InSAR measurements were gathered separately, then transformed to a common projection and superpositioned in GIS as to compare temporal time series. Where the information does not overlap fully the closest dataset was used.

3 Results

We present in this section the deformation measurements produced by the InSAR technique in the project. Geodetical data have been obtained from the dam owners in parallel with the collection of remote sensing data, in order to compare and verify the results from the InSAR analyses.

Data that were obtained from the dam owners consisted principally of three datasets:

1. Subsidence data from the dams (historical and in parallel with the recording of remote sensing data)
2. GIS data, height models and dam drawings
3. Reports of dam safety (supporting documentation)

The data were used to evaluate the observed settlement in a historical perspective and the expected rate of settlement relative to the dam conditions. Deviations were checked against available dam safety reports.

The GIS data were used to locate measurement bolts and to compare the measurement series of the bolts with InSAR analysis carried out by Globesar. The results can subsequently be presented in a GIS system, giving greater understanding and precision.

Geodetic measurements give absolute values that are based on a predefined reference point outside of the dam area. The very nature of InSAR measurements is that they are relative. In order to obtain absolute measurements, it is necessary to define a fixed point that can be used as a reference point. This may be, for example, an area of fixed bedrock around the dam. An InSAR measurement point was selected for this study that lay closest to a bolt, in order to determine whether the measurements agree

3.1 THE RIEPPEJAVRI DAM

The Rieppejavri dam was completed in 1978 and is a 26 meter high rockfill dam that was constructed to complement the Skibotn hydropower facility owned by Troms Kraft. The reservoir also includes two smaller saddle dams on the northern shores of the reservoir.

Figure 5 Rieppejavri (Rihpojávri) dam located at 69.366, 20,424 in a tributary to Skibotnelva in Troms, Norway. Source Kartverket, norgeskart.no, 2015.

3.1.1 Geodetic measurements

During construction the Rieppejavri dam is well instrumented with 101 bolts, which have been measured every second year.

An initial quality control of the received datasets gave that the datasets were inconsistent. In addition to known errors, such as a bolt having been destroyed by a NATO tank taking a shortcut over the dam, some inexplicable numbers came up. Further analysis gave that an unknown local datum and projection had been applied. After an extensive investigation in trying to rectify the historical data, these large errors were identified. Troms Kraft and Sweco initiated interviews and verification of factual data and records that gave that the equipment in use was out of date, un-calibrated and that there had be a monitoring gap when the surveyor initially in charge had retired 2006.

As a consequence the geodetic measurements gave no data for verification purposes for the Rieppejavri dam. The InSAR analysis was used to document the deformation of the dam body, even though the accuracy in the InSAR readings in this case could not be verified due to the lack of reliable geodetic data.

3.1.2 InSAR analysis

Figure 6 presents deformation measurements of the Rieppejavri dam and its surroundings. A series of 55 TerraSAR-X Stripmap mode remote sensing measurements taken during snow-free periods in the years 2009-2013 was used to produce the deformation data. Figure 6 shows the average rate of displacement in mm/year, estimated by the PSI-technique. The measurements were taken when the satellite was in a south-bound orbit and directed obliquely (approximately 30° from the vertical) to the west, i.e. the measurements are approximately in the downstream direction. The rate of deformation at the dam itself is 1-2 mm/year. Deformation with a rate of 2-5 mm/year has been measured in terrain east of the main dam at Rieppejavri. Approximately 2000 measurement points have been produce solely on the dam in the image below.

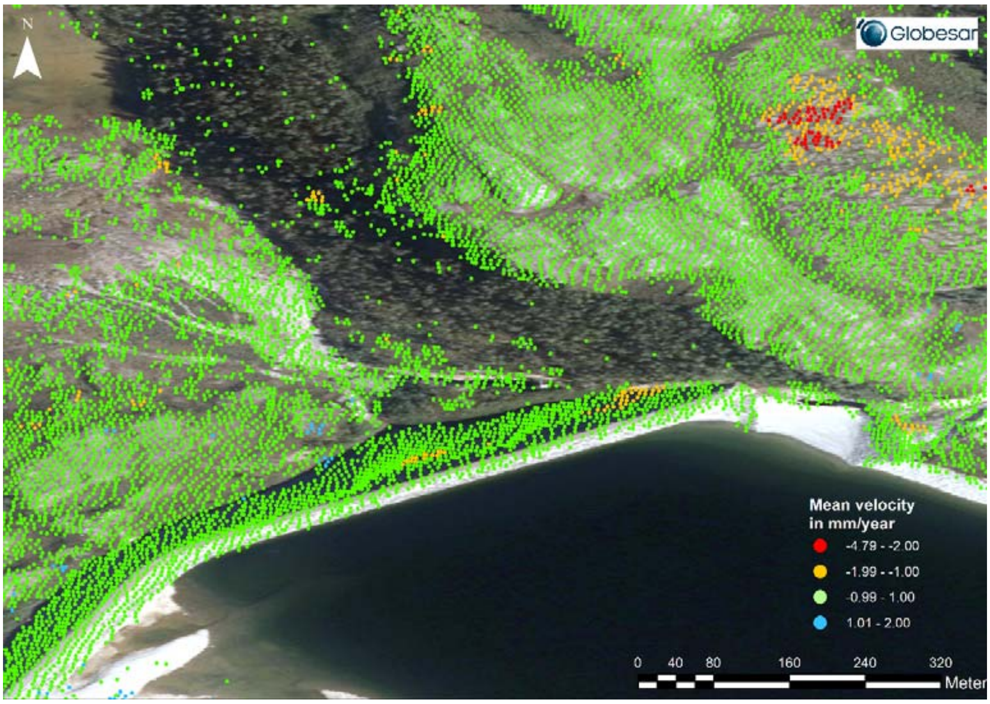


Figure 6. The figure shows the average rate at the Rieppejavri dam and its surroundings in the years 2009–2013. Red and yellow points show movement away from the radar, while blue points show movement towards the radar.

3.2 THE AKERSVATN DAM

Akersvatn dam in Storakersvatnet is a 53 meter high rockfill dam constructed 1964-1967 and has recently undergone extensive rehabilitation to meet stricter safety guidelines from the Norwegian Water and Energy Directorate. The rehabilitation involved dam heightening and rip-rap upgrades on both sides of the dam.

Figure 7 Akersvatn dam located at 66.21, 14,30 near Rana Nordland , Norway. Source: Kartverket, norgeskart.no, 2015.

3.2.1 Geodetic measurements

Akersvatn dam has two sets of bolts, 15 core bolts at the dam crest, measured every year and 84 deformation bolts which are controlled every five years.

Even though there were annual data for the core bolts, these were not used for independent correlation as an initial quality control of the datasets showed some irregularities. For the deformation bolts Statkraft were able to supply measurement data from 2009 (directly following the rehabilitation) and 2014 which coincided with the InSAR measurements.

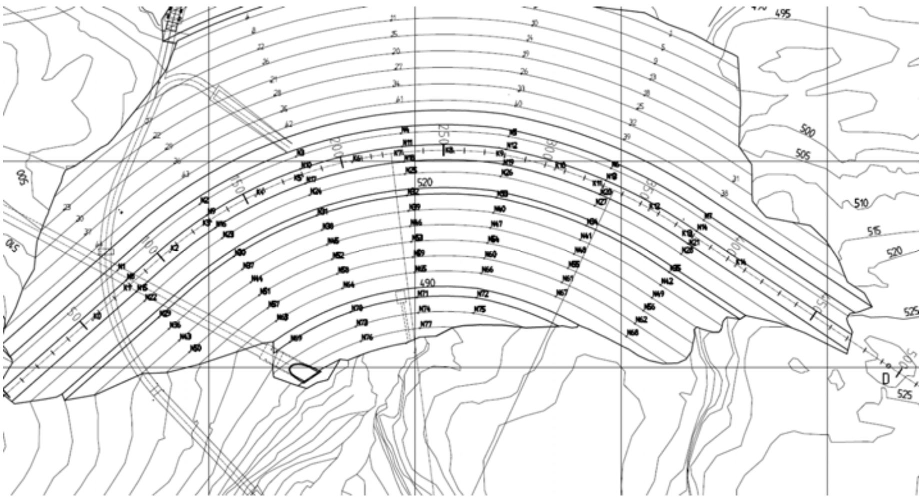


Figure 8. As-built deformation bolt plan from the rehabilitation 2009.

3.2.2 InSAR analysis

Figure 9 shows deformation measurements for Akersvatn dam. A series of 24 TerraSAR-X Stripmap mode remote sensing measurements taken in 2013 and 2014 were used to produce the deformation map. Approximately 7,500 measurement points were produced solely on the dam using the PSI technique. The colour scale illustrates the deformation measurement at each measurement point. The radar measurements were taken when the satellite was in a south-bound orbit and directed obliquely (35o from the vertical) to the west. This means that the subsidence has been measured approximately in the downstream direction, which commonly is the direction of the largest deflection in a dam.

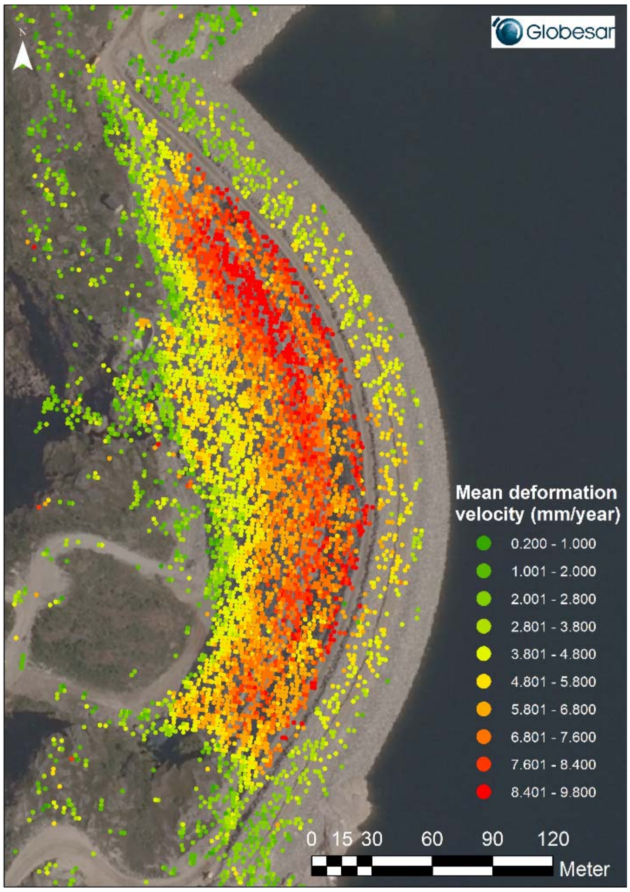


Figure 9. The figure shows the average deformation at the Akersvass dam measured by remote sensing InSAR (PSI). The total number of measurement points at the dam is approximately 7,500.

A time series has been produced for each measurement point that shows the development of the deformation at the point. Figure 10 shows an example of a time series that illustrates the development of deformation for a measurement point at the Akersvass dam. A deformation time series has been included for each measurement point produced by InSAR. This makes it possible to carry out detailed analysis of the deformation and trends.

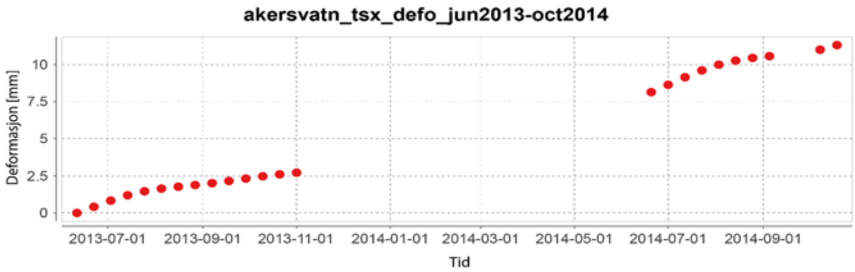


Figure 10. An example of a time series that shows the development of subsidence at a point measured by the remote sensing InSAR technique at the Akersvass dam. The number of points in the figure corresponds to the number of remote sensing measurements included when producing the deformation data. The time series contains interruptions due to snow cover during the winters.

3.3 THE SVARTEVATN DAM

Svartevatn is a rockfill dam with a central moraine core. Upon completion in 1968, the 130 meter high dam was the largest dam in Northern Europe with a dam volume of over 4.7 million m^3. The 81 meter regulating amplitude and 1398 million m^3 storage (Equivalent of 727 GWh) provides a strategical asset for the operator, Sira-Kvina.

Figur 11. Svartevatn dam located at 59.13, 6,90 in the upper Sira catchment, Norway. Source NVE Atlas, atlas.nve.no, 2015.

Due to increased regulatory demands with respect to dam safety, the dam underwent extensive rehabilitation 2012-2014, which impacts the results of the analysis of the dam.

3.3.1 Geodetic measurements

After the completion of the rehabilitation works, the dam will be instrumented anew in 2015. As a consequence there are no geodetical data available from the traditional measurements for verification purposes.

During the construction, the dam surface has been mapped by laser for design verification, but the data has unfortunately not been made available to the project. Thus there is no verification data for the Svartevatn dam.

3.3.2 InSAR analysis

Figure 12 shows the total deformation at the dam after refurbishment was completed in the autumn of 2014. Approximately 5,000 measurement points were produced on the dam alone, using nine remote sensing measurements from the TerraSAR-X satellite. Green points are stable, while red/orange/yellow areas correspond to approximately vertical subsidence. The poor coverage for the upper parts of the dam is due to ongoing refurbishment work. The refurbishment had been completed in areas for which we have coverage (points). InSAR processing for this dam was difficult, since refurbishment was being carried out as the data was recorded, such that the coherence (quality of the signal) varied. It would be a great advantage to carry out one further full season of measurement after refurbishment in order to document subsidence.

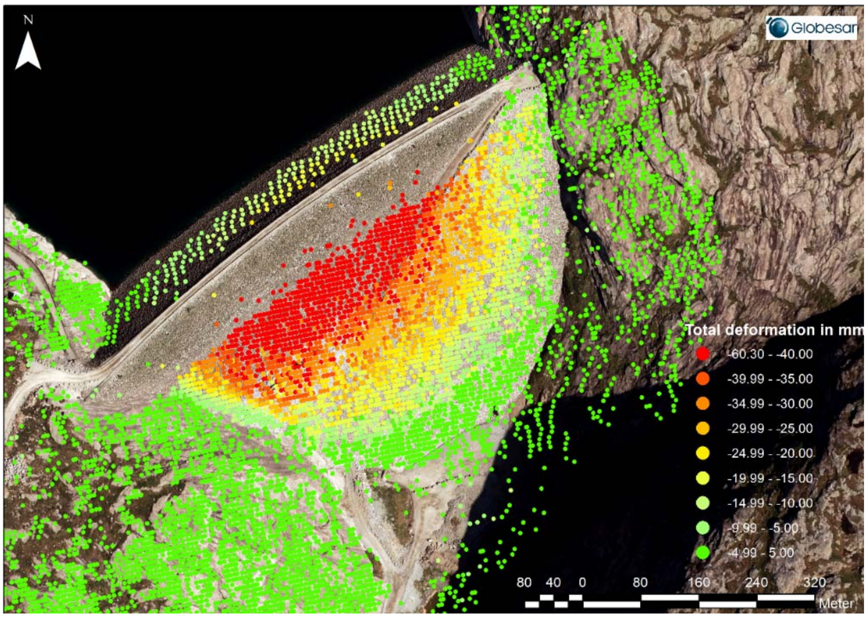


Figure 12. The figure shows total deformation produced by the InSAR method at the Svartevatn dam, from the autumn of 2013 until the autumn of 2014.

3.4 THE AJAURE DAM

Ajaure is located in the upper reaches of Ume River in northern Sweden. The 46 meter high dam was constructed 1964-66 and contributes to regulating the Ume river cascade with its 5500 million m^3 reservoir volume. In 2014 this cascade produced 6.8 TWh, slightly more than 10% of Sweden's national hydropower production.

Figure 13. Ajaure dam located at 65.51, 15.63 in the upper Ume River, Sweden. Source Lantmäteriet/Metria, 2013.

The dam was rehabilitated in 2001-2002 and has for a long time been the focus of Vattenfalls dam safety improvement program.

3.4.1 Geodetic measurements

The dam owner at Ajaure had an increased focus on the accuracy of the deformation measurements during the period of the project, which can be seen in a significant reduction in the variability of the observations from 2012 onwards.

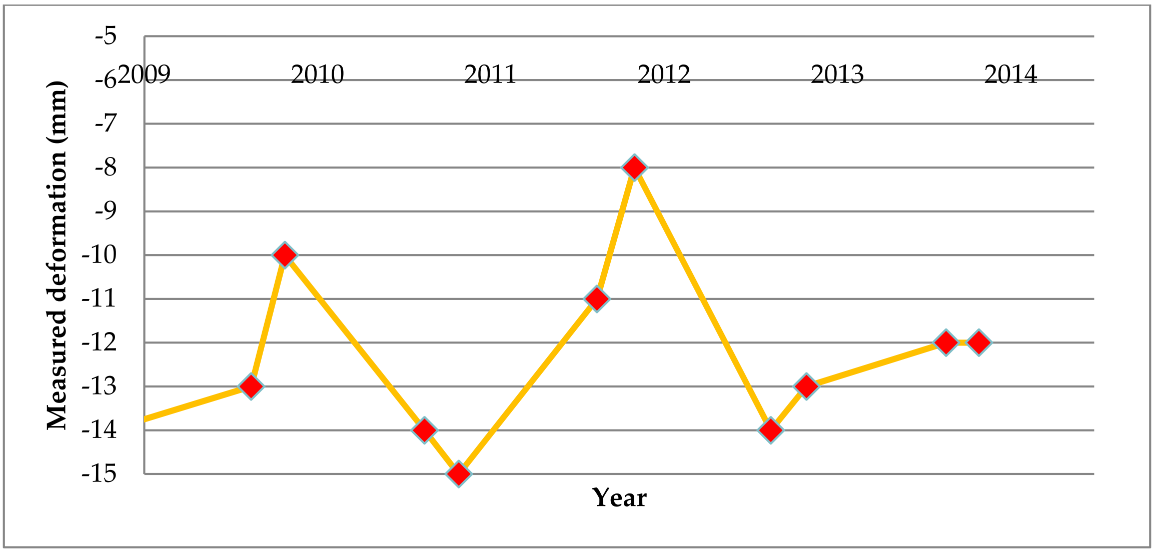


Figure 14 Geodetic measurements at Ajaure.

3.4.2 InSAR analysis

It was possible to produce approximately 25,000 measurement points at the dam with the satellite that was used, the TerraSAR-X in Spotlight mode, with a resolution of approximately 1 x 1 m per pixel. A subsidence of approximately 1 cm was recorded in the red area of the dam between June 2013 and October 2014. Figure 15 shows the deformation measurements for the Ajaure dam. Descending and ascending measurement geometries have been combined for the Ajaure dam, which enables distinguishing between vertical (top left image) and east-west horizontal movement (bottom left image). The latter is illustrated with total displacement and the angle of the displacement. Larger-scale images from Figure 15 are presented in Appendix B.

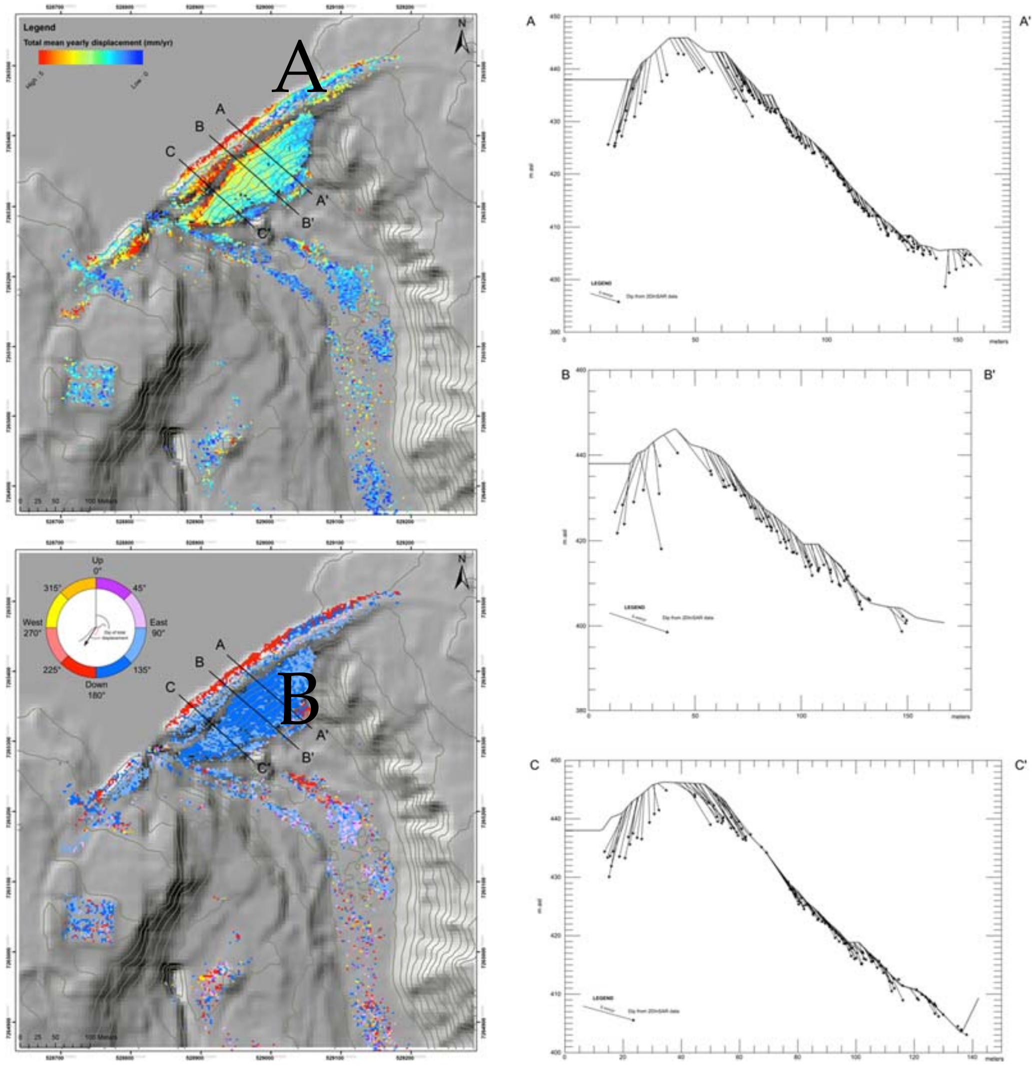


Figure 15. Figure A shows the total average displacement by combining ascending and descending geometries. Figure B shows the angle of displacement measured in the east-west plane. The profiles A-C illustrate the total displacement (shown as length of the arrows) and the direction, projected onto the direction of the profile.

4 Analysis and verification

One central conclusion of this pilot project is the challenges associated with repeating accurate and robust manual geodetic measurements of deformation. Several years can pass before the measurements are repeated, and this means that the measurements are seldom repeated by the same company or personnel, and seldom with the same equipment. This results in a certain degree of divergence in accuracy between measurements. It is often a challenge to verify the quality of the measurements, since a divergence in the measurements does not become apparent until the next measurement has been carried out, something that makes it extremely challenging to determine the quality of the first set of measurements. This emphasises the importance of carrying out geodetic measurements in a correct and accurate manner, with a good repeatability, such that they can serve their purpose of monitoring dam stability.

Just as is the case for geodetic measurement methods, it is challenging to draw conclusions from InSAR measurements simply from one measurement in time and space. The InSAR method is based on a series of measurements in time, such that high accuracy and a high density of measurement points can be ensured. The fact that the InSAR method requires regular measurements in time contributes to a user obtaining data of a higher quality in the form of more frequent measurements in time and space, and this in turn simplifies the analysis of trends and the general evaluation of dam safety.

At least two geodetic measurements are required in order to be able to compare geodetic measurements with InSAR measurements in a relevant coordinate system. In order to verify the results, the geodetic measurements must be highly accurate over a long period of time, and this has proved to be a challenge in this project. Even though it has been difficult to find overlapping geodetic measurements of sufficiently high quality, it has been possible to reach two general conclusions:

- The total deformation measured by InSAR agrees well with the expected rates of subsidence during the period of remote sensing measurement.
- At dams where manual geodetic measurement was carried out with high precision several times per year, the comparison with InSAR shows that the trends in subsidence agree well, supporting the validation of the method.

The dams of Ajaure and Akersvatn can be used to illustrate the points above.

4.1 AJAURE

The best case is Ajaure where the dam owner had increased focus on the accuracy of the subsidence measurements during the period of the project, which can be seen in a significant reduction in the variability of the observations. This becomes apparent when newer measurements are compared with historical data. The significant reduction of the differences between measurements reflects also the improvement programme set up by the dam owner, where the focus in recent years has been on the instrumentation of dams.

The deviation between traditional measurements and the InSAR data towards the end of 2013 shows that snow cover influences the measurement results obtained by remote sensing. After the snow melted in 2014, the data series again agrees well with manual measurements, with a deviation of less than 2 mm.

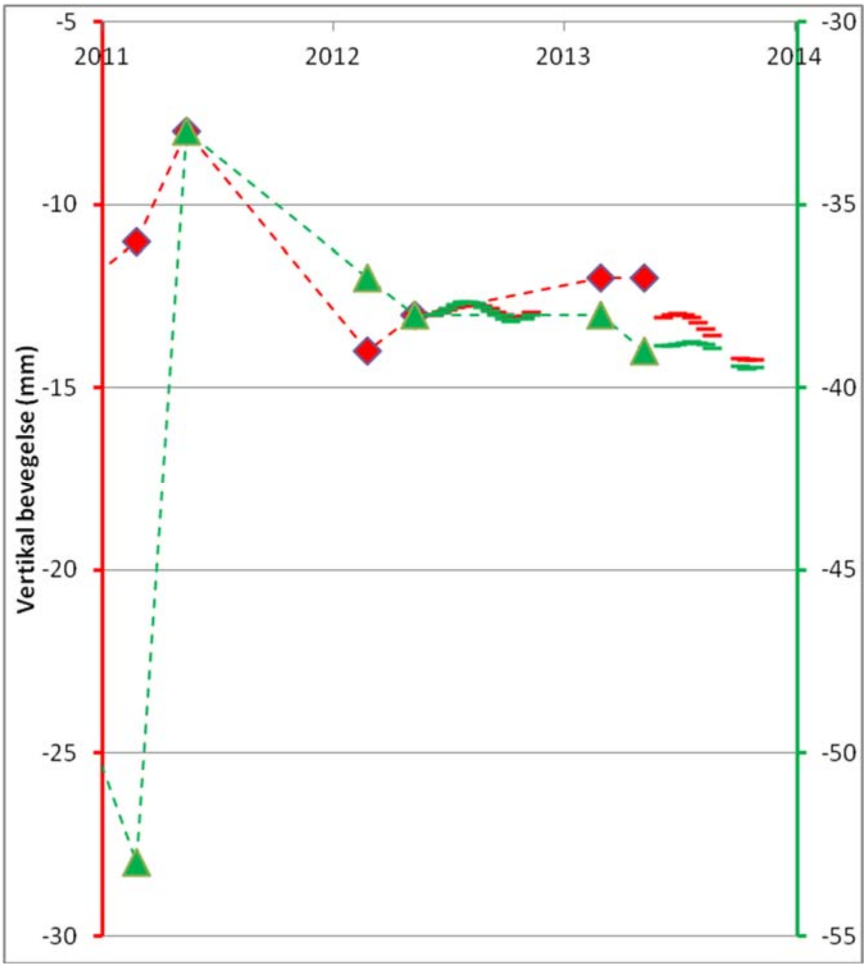


Figure 16. Geodetic measurements of two points in the highest part of the dam with deformation in millimetres in 2012-2014 compared with InSAR data for 2013-2014. The deformations along two axes are shown, where the uppermost series (point 40) has been plotted on the left side in red and the lowermost (point 36) on the right side in green. The results for both points agree extremely well.

In previous studies, the dam has shown a pattern of plastic-elastic deformations with cyclical incomplete stretch deformations. The deformation shows itself in a wave pattern that cannot be completely documented by manual measurements, due to their low resolution. A similar wave pattern can be seen in both the manual observations and the InSAR series, without it being possible to correlate this directly with the water level in the reservoir. One explanation may be a time-varying component of the process, while another is a possible 3D effect that requires additional study to be established.

4.2 AKERSVATN

A second example of the verification process is Akersvatn. Figure 17 below shows measurements from three deformation bolts mounted close to the crest of the dam. Two measurements carried out after the refurbishments in 2009 and 2014 are compared with two seasons of InSAR measurements, 2013 and 2014.

Figure 17. Deformation bolt measurements in 2009 and 2014 (start of 2014 InSAR measurements) of N11, N17 and N14 compared with the relevant InSAR measurement series in 2013 and 2014.

The results agree well with an interpolated estimated subsidence shown by dashed lines. The estimated deformation is relative to the fill height at the relevant point.

5 Discussion

5.1 ON DEFORMATION MEASUREMENTS

As this study illustrates, the philosophy of instrumentation has been applied differently at the dams studied. There is still significant movement to be tracked and spatial as well as temporal variations have been found through the application of InSAR. These variations illustrate the weakness of using a limited amount of deformation bolts.

The study also demonstrates the need to continuously verify measurements and that there is a wide spread in accuracy and quality of geodetic measurements.

Most importantly, the accuracy of deformation measurements must be relative to the magnitude of the deformation. For older dams, the surface deformation may be as low as millimetres per year, after the dam has settled following refurbishment, or when a dam has been completed. In cases in which subsidence measurement is used in the work with dam safety, the expected accuracy of the measurements must be better than the expected deformation. The reliability of the geodetic measurements with respect to accuracy was a challenge for the dams that was studied in this pilot project. The limited accuracy of manual geodetic measurements is a clear problem, as is also the relatively low frequency of measurements, which is largely controlled by industry regulations and codes of practice. In cases in which it is necessary to measure the elastic and seasonal trends, measurements must be carried out several times per year for several years.

5.2 TECHNICAL ASPECTS OF THE STUDY RESULTS

Even though it was not possible from a statistical point of view to use the geodetic measurements in the project to verify the accuracy of the InSAR measurements, the results indicate that the InSAR method gives significantly greater accuracy for deformation measurements than traditional manual readings.

Many publications and projects have demonstrated that InSAR is an extremely accurate measurement method. **Figure** 18 shows an example that demonstrates the accuracy of InSAR measurements, for the monitoring of a mountain area in Norway. Several satellite reflectors were installed and anchored in the mountain area in order to verify the accuracy. The reflectors function as perfect radar targets ("*persistent scatterers*"), and have been covered such that no snow can accumulate during the winter. This makes it possible to measure displacement throughout the year. Permanent GPS stations have also been installed, and these measure the displacement of the reflectors continuously. The time series shown in **Figure** 18 is a comparison of InSAR and GPS measurements for the reflectors during approximately 6 years. Remote sensing data from the Radarsat-2 satellite have been used, with a repetition time of 24 days. The comparison shows clearly that InSAR measures the same trend as GPS, and that the accuracies of the measurements are in the millimetre range.

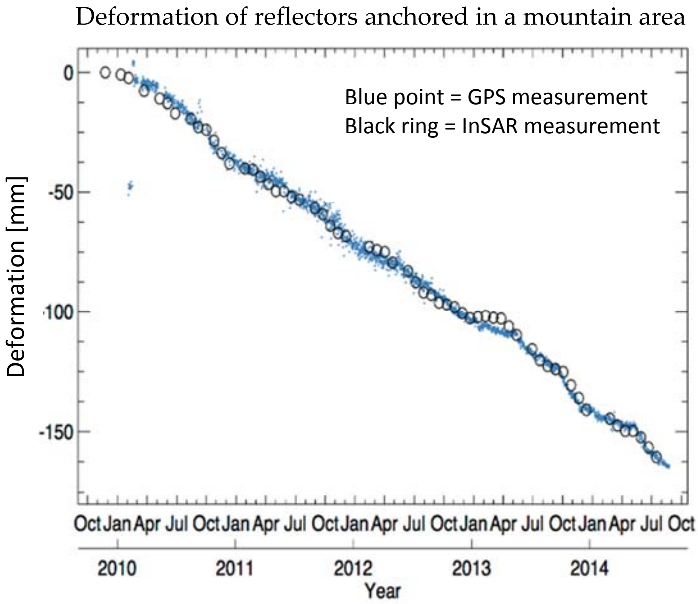


Figure 18 - Verification of the accuracy of InSAR measurements by comparison with GPS

InSAR measurements have a higher frequency than geodetic measurements, which makes it possible to ensure the quality of deformation trends in both time and space, by, for example, monthly updates during the snow-free period of the year. The InSAR measurements at the Akersvatn dam, as is the case also for the Ajaure dam, agree well with the expected rate of deformation, even though the time coverage of manual measurements is insufficient to be able to statistically verify this.

All InSAR time series show also that there is very little variation in the measurements, which indicates that the measurements are only slightly sensitive to external influences. This is in contrast to the case for manual measurements.

The arguments in favour of InSAR are that priority must be given to measurement methods that are: simple, robust, insensitive to external influences, with a long lifetime, precise, and that give results that are easy to interpret (Bulletin 158, ICOLD). The possibilities of being able to provide historical data to study long-term deformations during the lifetime of a dam increase as more satellites equipped with radar systems come into operation since the first radar-equipped satellite was launched early in the 1990s.

5.3 ECONOMIC CONSIDERATIONS

There are two components of the costs for using InSAR measurements: The first component is directly related to which remote sensing data (the number of measurements and their resolution) are used in producing deformation data, while the second is related to the production and interpretation of the deformation results.

One the first aspect of remote data, the European Space Agency (ESA) has invested heavily in launching satellites equipped with radar systems, and these are to give priority to measurements in Europe where the data will be recorded and stored for common access. This means that satellites now carry out continuous measurements over Europe, and it is not necessary to order such measurements in advance. Thus, regular remote sensing measurements are available in ever increasing quantities and can be used for InSAR. The costs for the data are minimal, since the ESA applies an open data policy. The density of measurement points that can be obtained from ESA satellites is limited, and varies from one area to the next. However, if the density of measurement points is insufficient, alternative commercial satellites (such as TerraSAR-X) are available that offer measurements with a resolution as low as 0.25 x 0.25 m per pixel.

The second aspect on analysis and interpretation of the results will probably not see a similar fall in costs as it is more skilled labour intensive. Costs are somewhat relative to scale and could be expected to fall somewhat as the number of dams covered increase. Further, as a market is established for InSAR analysis, competition could bring down the costs over time.

The benefit and the added value that arise from using InSAR measurements depend on the object or dam that is to be measured. Dams whose behaviour is problematic require frequent measurements, and this may lead to manual observations becoming extremely expensive. As the cost of remote sensing data falls, InSAR can become a competitive alternative for small and standardised dams, particularly in situations in which the quality of manual geodetic measurements has proved to be a problem.

5.4 REQUIREMENTS ON AND BY REGULATORS

Requirements on monitoring dams differ from one country to the next, but are converging towards higher safety standards in order to meet society's increasing requirements for risk management. InSAR measurements contribute to more objective measurements (Grzanic, 2014) and InSAR can be used as an independent or supporting measurement method to verify measurements obtained from other methods. This opens the possibility that InSAR be given a more permanent place in monitoring dam safety, together with other traditional measurement methods.

6 Conclusions

This project has demonstrated that InSAR produces a dense network of measurement points over the dams, something that contributes to a considerably more complete coverage than currently used manual geodetic methods. InSAR achieves this without any previous installations or presence at the dam. The advantages of InSAR make it possible for deformation measurement to progress from being a long-term method with limited accuracy and density of measurement points, to become a method that allows periodic monitoring with a high density of measurement points in time and space to be carried out. This is a valuable contribution to the work with dam safety.

Satellite-based InSAR brings other advantages that have not been the focus of this project. As a consequence of the ability of satellite-based InSAR to cover large areas while maintaining a high density of measurement points, it is possible to measure neighbouring mountain areas, reservoirs, dams and other infrastructure in an efficient manner in order to identify and monitor weaknesses in the terrain and infrastructure that may constitute risks for the general operation of the dam. Thus the method opens up possibilities to at a reasonable cost monitor waste or remote areas that are technically difficult, as well as costly, to monitor manually. It opens up the possibility to back-track and verify the conditions before an incident, to investigate if there has been any deformations in the area in connection with the incident. It is also suitable to monitor dams where large seasonal, or elastic, variations in the deformation pattern can be seen, which may require costly and frequent geodetical monitoring to comprehend.

It must at the same time be emphasised that InSAR cannot give direct information about processes such as internal erosion, washing out of material from the impervious core or problems with the foundation before the damage becomes sufficiently large to show itself as displacements at the dam surface.

Requirements on monitoring dams differ from one country to the next, but are converging towards higher safety standards in order to meet society's increasing requirements for risk management. In summary, this project has shown that satellite-based InSAR is a measurement method that provides a new perspective on subsidence measurement, with accurate and objective measurements. The introduction of InSAR as a measurement method in the hydroelectric power industry would radically improve the possibilities of reliable and precise monitoring of surface deformations. InSAR can be used as an independent or supporting measurement method to verify measurements obtained from other methods. This opens the possibility that InSAR be given a more permanent place in monitoring dam safety, together with other traditional measurement methods. A gradual increase in the use of this measurement method at dams can contribute to a better understanding of the analysis of trends, and improve the general work with dam safety..

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INSAR ON EMBANKMENT DAMS

In this study the potential of Interferometric Synthetic Aperture Radar (InSAR) to provide timely settlement measurements in high spatial resolution has been tested on four dams in Norway and Sweden.

The results show that InSAR provides data that is consistent with the settlement patterns expected and with the manual geodetic ground measurements for the dams of Akersvatn and Ajaure. The study shows that the InSAR methodology can give reliable settlement data with little variation and high temporal and spatial resolution for dams.