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GPS AND INSAR TECHNOLOGIES: A JOINT APPROACH FOR THE SAFETY OF LAKE SAREZ

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RÉSUMÉ

Le lac Sarez, au Tadjikistan, s'est formé en 1911 lorsque qu'un effondrement catastrophique engendré par un séisme a recouvert le village d'Usoy sous une masse de 650m de haut, obstruant la rivière Murghab. Le lac ainsi formé au cœur du massif du Pamir, de 60 km de long, avec un volume de 17 km3, est retenu derrière la digue naturelle d'Usoy qui se trouve être le plus haut barrage au monde.

En raison de ses dimensions, les informations relatives au barrage d'Usoy se réduisent à des hypothèses basées sur des observations et l'analyse de quelques paramètres recueillis dans le passé. Afin de réduire le risque lié à Sarez, un système moderne d'auscultation couplé à un système d'alarme a récemment été mis en place dans le cadre du "Projet de réduction des risques du lac Sarez". Le système d'auscultation couvre également une masse instable située 4 km environ en amont du barrage. Un effondrement dans le lac provoquerait d'énormes vagues qui pourraient menacer la stabilité du barrage ou tout au moins modifier son régime de percolation.

Le présent article décrit les investigations faites autour de cette masse instable, en particulier sa géologie, les risques q ui lui sont associés et le programme de mesures qui inclue des mesures GPS des déplacements. Afin d'avoir une meilleure connaissance de l'évolution des mouvements de cette masse et pour corréler les investigations géologiques avec les mesures du système d'auscultation, une autre approche était nécessaire. La technologie InSAR, et plus spécifiquement PSInSAR™, a été retenue. L'article présente la méthodologie et les résultats obtenus. Une comparaison des résultats InSAR et GPS est présentée et certaines conclusions sont tirées de cette approche conjointe.

ABSTRACT

Lake Sarez in Tajikistan was formed in 1911 when a massive, earthquake-triggered landslide buried the village of Usoy under a 650 m high obstruction which dammed the Murghab River. The resulting 60 km long lake containing over 17 km^3 of water is located behind the so-called Usoy natural dam in the Pamir range, the highest dam in the world.

Owing to its huge mass, the level of knowledge of the Usoy dam is reduced to hypothesis based on observations and analysis of few parameters gathered in the past. In order to reduce the risk related to Sarez, a modern monitoring system, coupled with an early warning system has been installed, recently, in the frame work of the "Lake Sarez Risk Mitigation Project". The monitoring system covers an unstable slope, located some 4 km upstream of the dam, which, if it collapsed into the lake, would create waves that could threaten the stability of the dam or, at least, modify its seepage regime.

This paper describes the investigation of the unstable slope hazard discussing the geology of the area, the risks associated with a potential failure, and the monitoring program which includes the use of GPS. In order to gain a better knowledge of the evolution of the movements of the unstable mass and to correlate the geological findings with the first results of the monitoring system, another approach was required. InSAR, specifically the advanced form - PSInSAR™, offered this alternative investigative technique. The paper presents the methodology and the results obtained. A comparison of InSAR and GPS measurement is made and conclusions can be drawn from this joint approach.

1. INTRODUCTION

Lake Sarez in Tajikistan was formed in 1911 when a massive earthquake-triggered landslide buried the village of Usoy under a 650 m high obstruction which dammed the Murghab River. The resulting 60 km long lake containing over 17 km^3 of water is located behind the Usoi natural dam in the Pamir range, the highest dam in the world.

Although the safety of the lake has been studied over many years, significant gaps and inconsistencies existed in the data available. Despite this lack of data, however, it was clear that, in the event of failure of the dam, the risk to the downstream population living in the Bartang and Pianj river valleys was high. The following actions have been required to mitigate the risk in the framework of the Lake Sarez Risk Mitigation Project (LSRMP):

- the design and implementation of a monitoring and early warning system in order to follow up the long term evolution of the natural structures as well as to reduce the consequences of any uncontrolled behaviour of the dam (Component A)
- identification and construction of safe havens as well as training the vulnerable communities under a disaster preparedness programme (Component B)
- the preliminary studies of long term solutions to minimise the probability of failure (Component C)

Internal strategies to mitigate the risk of failure of the Usoi Dam were developed by the UN/ISDR (2000) mission. A global risk analysis (Droz *et al.*, 2006) of the situation helped, first, at identifying the various hazard phenomena related to Sarez that could endanger the population living downstream and, second, at defining a monitoring and an early warning system.

2. LAKE SAREZ AND USOY DAM

2.1 The highest dam in the world

The Usoy dam has a typical cross section with an overall upstream slope of 1:3 and a downstream slope of 1:7. It is composed of two basic material types:

- Carboniferous shales and sandstones, ranging in size from tens of metres to tens of centimetres. This zone occupies the surface of the central and left side of the dam and represents the first waves of the landslide.
- Triassic material with size ranging from meters to centimeters set in a matrix of sandy silt. This zone occupies the surface of the extreme right abutment of the dam (origin of the collapse) and represents the last waves of the landslide

The internal composition of the Usoy Dam remains unknown. According to surface observations, huge and abrupt variations in granulometry are to be expected.

The lake level has only slightly increased over the years. The average annual inflows are similar to the corresponding outflows from seepage springs, located on the downstream face of the dam. Their total discharge varies between 35 and 85 m³/s.

Figure 1. Aerial view of Usoy dam. The RBS is in the background.

2.2 The right bank unstable slope

Some 4 km upstream of the Usoy dam, a large unstable slope has been identified and is referred to as the Right Bank Slope (RBS). The slope is mainly covered with loose material (silty-sandy-blocky material resulting from the weathering of the bedrock, and some glacial till deposits). This loose material shows a certain cementing due essentially to the harsh climatic conditions. The bedrock along which the toe of the slope is aligned – from its high degree of disintegration – is interpreted to represent dislocated material from a former rockslide (see Figure 2). It consists of hard and fractured detritic carboniferous rocks of the Sarez Formation (sandstones, schists, slates, etc.) Should it collapse into the lake, this unstable mass would create waves that could threaten the stability of the dam or at least modify its seepage regime.

Figure 2. Right Bank slope (RBS) some 4 km upstream of the Usoy dam.

Measurements performed across opened cracks on the slope, using special extensometers monitoring both extension and inclination, have been made since the late 1980's until the present by the Geological Institute of Tajikistan. The results indicate movements of approximately 10 cm/year. But the extent of the unstable mass was not clearly assessed and, moreover, assumptions were made of a deep seated landslide, with potentially catastrophic consequences, without real evidence. Although attempts were made to drill deep cores, extreme difficulty of access and the harsh environment of the region proved too great a challenge and this work could not be completed.

3. HAZARD ANALYSIS

3.1 Hazard scenarios

The detailed analysis of data that were available or were collected during complementary site investigations led to the conclusion that the global instability process (sudden outburst of the dam) resulting in an extreme flooding scenario can be directly excluded. Although other hazard scenarios are very unlikely, it was necessary to identify those that would help with designing a Monitoring and Early Warning System. These scenarios are summarized in a fault tree analysis.

3.2 Fault tree analysis

The fault tree shows that life threatening floods in the Bartang Valley could be caused by:

- direct overtopping with or without external erosion due to a huge wave

- an internal erosion process

External erosion (landslide and obstruction on the downstream face of the dam) can be induced by modification of the internal flow process and the appearance of new springs.

Huge waves can be generated by the right bank landslide that may or may not be triggered by an earthquake.

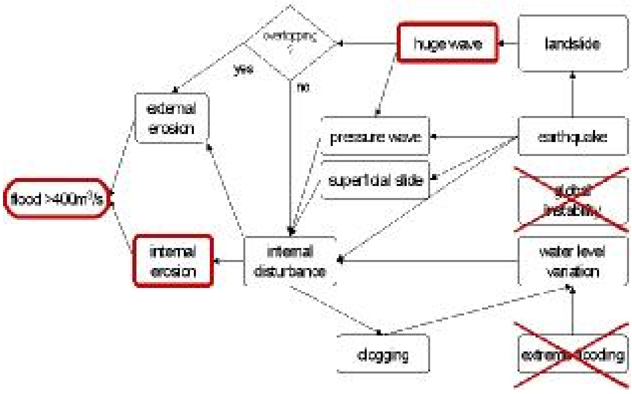


Figure 3. Fault tree analysis of the Usoy dam: major hazards are identified

Internal erosion can be induced:

- by a pressure wave due to the landslide or an earthquake
- by a huge wave that does not overtop the dam but disturbs the internal equilibrium
- by exceptional water level variations
- by a clogging of the core of the dam that leads to a water level variation (a gentle overflow can be excluded since the upper part of the dam is extremely permeable)

Risks related to internal erosion and piping processes are extremely low and do not present immediate dangers for the Bartang Valley population. Nevertheless, slow modification of the seepage area will go on and, therefore, must be monitored.

4. MONITORING USOY

4.1 General layout

A new Monitoring and Early Warning System (M & EWS) was installed in 2004. Components of the Monitoring System are used for triggering alarms and are integrated into the Early Warning System. The Monitoring System comprises mainly the following elements:

- the Monitoring Units (MU's) with their own independent power supply
- the Data Acquisition System in what is referred to as the Dam House (CU)
- the Supervisory Control and Data Acquisition System (SCADA) with data storage, analysis and decision support software in Dushanbe.

All data and remote control of the systems are communicated through the Inmarsat Mini C satellite system, or cables for local short distances. Table 1 and Figure 4 present the equipment of the MU's.

Table 1. Monitored parameters and corresponding equipment

Monitored parameter	Equipment
Right Bank Slope (RBS)	GPS manual measurement
earthquake	3 strong motion accelerographs
lake level	pressure cell measurement of water level
abnormal wave	pressure cell used to capture abnormal wave height
dam body movements	GPS manual measurement
outflow discharge	automatic radar sensors over the river
	flow meter for calibration
flood occurrence	flood sensors to detect early occurrence of high flows
Meteorology	measurements of basic meteorological parameters

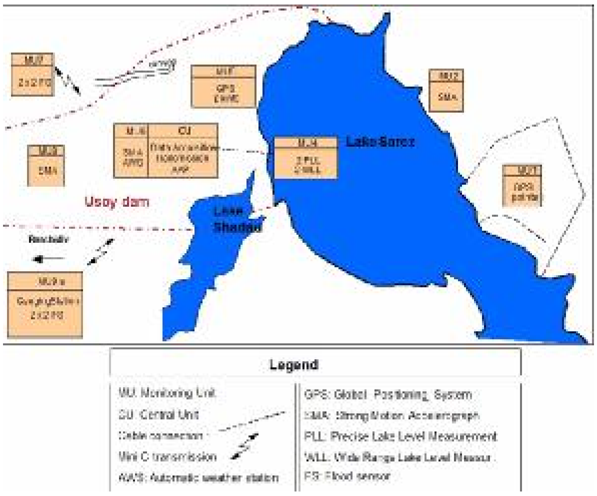


Figure 4. General layout of M & EWS instrumentation

4.2 Monitoring the right bank

Among the numerous parameters collected and recorded by the M & EWS, the movements measured on the RBS are essential to assess the hazard related to the unstable mass. These movements are measured 3 times a year by the mean of GPS measurement stations (Figure 5). They clearly indicate movements towards the lake. Measured displacements varied between 6 and 16 centimeters per year during the period 2004-2006. The movements on the RBS are in complete accordance with those measured in previous years. These movements are measured on the surface of the slope and thereby, do not give a complete idea of the unstable mass. Installing inclinometers and drilling deep cores are very expensive and extremely difficult to achieve owing to the remoteness and ruggedness of the region.

Figure 5. Measurement of a GPS stations on the RBS

4.3 GPS measurement results

The location of the RBS GPS stations is shown in Figure 6

The Figure 7 illustrates the movements of these GPS points projected on a cross section defined according to the highest topographical gradient. From this graph it is clear that the movements are parallel to the slope.

This finding corroborates the hypothesis that the general movement is a translational surface movement: no evidence of a deep-seated landslide can be found from this analysis (a deep-seated movement would have shown larger vertical components of movement at the top GPS stations and larger horizontal motion at the lower GPS stations, indicating a circular sliding surface). Most likely, it indicates creep of the sedimentary cover of the slope. The last movements measured in August 2006 point out important vertical movements of most of the stations located along the cliff overlooking the lake (R02, R03, R05 and R06). These GPS stations are located in the area of the rockslide at the foot of the RBS.

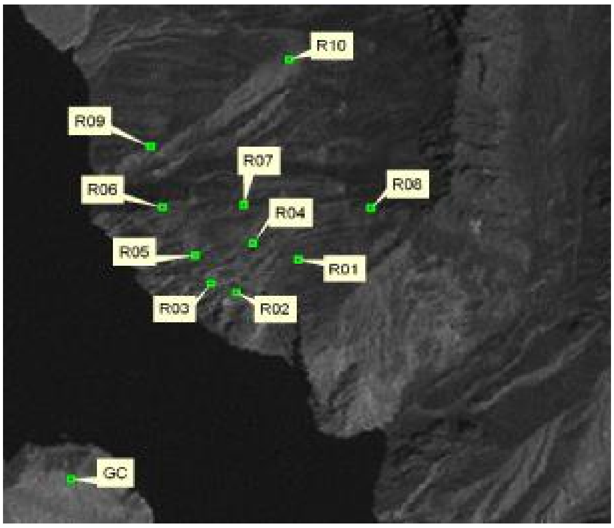


Figure 6: Location of GPS stations on the RBS

This illustrates that local settlements and slumping are in accordance with the geological model of behavior of the RBS.

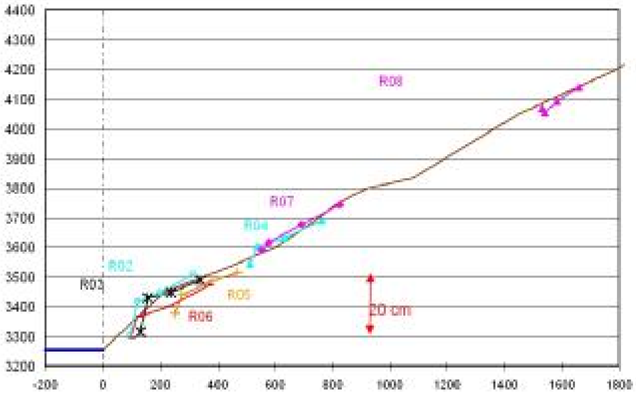


Figure 7. Cross Section of the RBS (length and altitude in meters) - displacements (2004-2006) x1000.

Nevertheless, it was necessary to compare these results with data obtained by other means and moreover data that could give information on the behaviour of the unstable mass before the first GPS measurements. Therefore, and because of the lack of subsurface information, an InSAR analysis was undertaken to assess the validity of the geological model.

5. INSAR ANALYSIS

5.1 Description

There are two basic forms of InSAR: Differential InSAR (DInSAR), which measures change from a single interferogram from two radar images, and Permanent

Scatterer Interferometry (PSInSAR^{TM}), a multi-interferogram approach that draws on the changes occurring between a series of radar images. DInSAR is particularly limiting when atmospheric influences are severe and when a continuous history of movement is required. PSInSAR™ overcomes the atmospheric constraints and is specifically directed at determining movement histories over periods of several years (Ferretti *et al.* 2000) (Ferretti *et al.* 2001).

PSInSAR™ searches the multiple image set for pixels within which are objects that consistently reflect radar signals throughout the entire data set. These objects may comprise rock outcrops, buildings, street lights, road signs among a wide variety of possibilities. They are referred to as Permanent Scatterers (PS). This particular technology, in a high-resolution form, was used to process data for this assignment.

Radar imagery acquired between 2003 and 2006, by the European Space Agency's Envisat satellite, presented an opportunity for InSAR to observe motion concurrently with GPS data.

The location of the RBS, representing a surface area of approximately 2 to 3 km², is shown in Figure 8.

Figure 8: The Lake Sarez area. The white circular outline represents the area studied by the InSAR analysis - the Right Bank Landslide.

5.2 Data analysis

The SAR data archive comprised a 23-image catalogued data set, acquired during the satellites' descending orbit, meaning that the platform was travelling from North to South.

Each Envisat image covers an area of about 100x100 Km, and is identified by the date of acquisition, a Track number - corresponding to the satellite orbit – and a Frame number, that specifies the 100x100 Km 'tile' within the Track. In this case, data from Track 5 – Frame 2837 were used, and the frame position is shown in Figure 9.

Figure 9: Relative position of the Envisat Track 5 - Frame 2837 Descending orbit. Lake Sarez RBS is indicated in the small square.

The data span the period from 2003 to 2006 with irregular time intervals between successive images. Table 2 lists all the available Envisat images in the dataset.

Table 2: List of Envisat images processed in this study. The master image is highlighted in red italics.

#	Mission	Date	Bn [m]	Bt [days]
1	Envisat	20030812	-838.92	-420
2	Envisat	20031125	-343.88	-315
3	Envisat	20031230	689.39	-280
4	Envisat	20040203	782.41	-245
5	Envisat	20040413	853.49	-175
6	Envisat	20040518	-102.07	-140
7	Envisat	20040727	234.91	-70
8	Envisat	20040831	233.43	-35
9	*Envisat*	*20041005*	*0*	*0*
10	Envisat	20041109	-453.51	35
11	Envisat	20041214	-169.12	70
12	Envisat	20050118	-294.68	105
13	Envisat	20050222	-503.81	140
14	Envisat	20050329	-827.28	175
15	Envisat	20050503	552.36	210
16	Envisat	20050607	-455.87	245
17	Envisat	20050712	780.88	280
18	Envisat	20051025	420.22	385
19	Envisat	20051129	-260.52	420
20	Envisat	20060103	145.27	455
21	Envisat	20060523	-475.19	595
22	Envisat	20060627	506.04	630
23	Envisat	20060905	384.42	700

Often, in areas of high elevation, snow impedes monitoring when it is present on the ground. At Lake Sarez, the area of interest (AOI) was not impacted by snow cover.

Starting with all the SAR images available, a set of differential interferograms is generated. This entails subtracting the phase of each slave image from the phase of the master image. The master image is selected for its baseline and other properties, in relation to all the other images (the slave images) in the data set. In doing so, the difference in signal path length between each pair of images is calculated. This difference is related to possible ground motion, but it also contains contributions that might arise from ionospheric and tropospheric effects, as well as possible orbit errors. These additional contributions have to be removed since they can lead to misinterpretations of the phase signal.

Estimation and removal of the atmospheric contribution from the interferometric phase is a key step of the PSInSAR^{TM} algorithm.

Once the signal phase has been corrected for these effects, any remaining changes in it directly reflect ground movement

5.3 Results

Figure 10 shows the estimated average velocity field for the AOI, on the right bank of Lake Sarez. The coloured dots, superimposed on a Landsat background image, correspond to the points where precise differential movement could be measured; these points are the Permanent Scatterers (PS). InSAR analyses yield relative displacement for which a reference point is needed that can be assumed to be motionless or for which an accurate history of movement is known. The purple circle located in the top left corner of the study area corresponds to the PS that was used as the reference point for the analysis. In this case, the point was assumed to be motionless, and all displacement measurements were computed with respect to this benchmark.

Figure 11 is a 3Dimensional view of the study area. It should be noted that all of the measured velocity values correspond to the projection of the actual motion of the point along the line of sight (LOS) of the satellite, in this case 23º off the nadir.

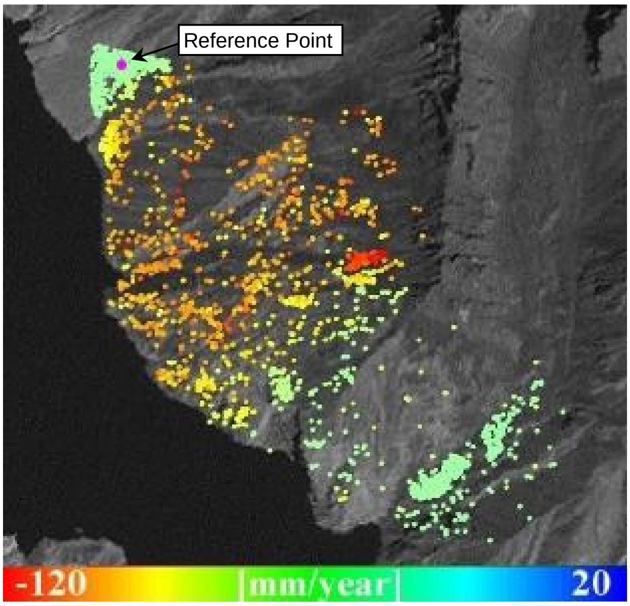


Figure 10: PS velocity map. For the purpose of visualization the velocity is colour-coded using a spectral scale whereby movement generally ranges from between +20 mm/yr (blue) and -120 mm/yr (red). Some PS may have rates of movement that exceed these limits. The purple circle corresponds to the PS that was used as the reference point for the analysis.

For each of the PS, a time vs. motion history is built up from the data. Examples of four time vs. motion series are illustrated in this paper. Their location is shown by the inset references in Figure 12 and the corresponding time series are shown in Figure 13.

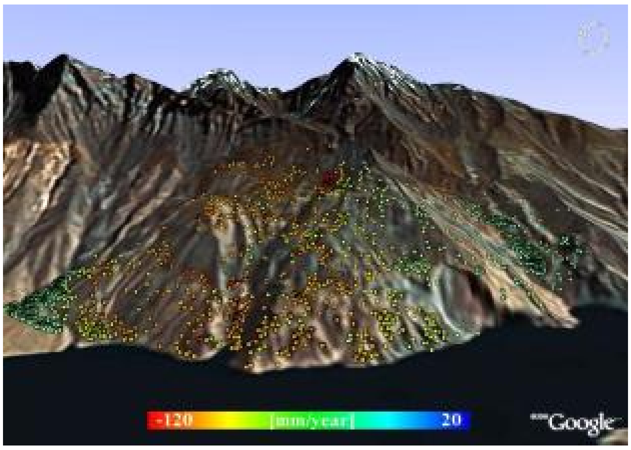


Figure 11: A 3-Dimensional perspective of the RBS showing the PS superimposed upon a background image of the AOI. The background image was created using Google Earth™

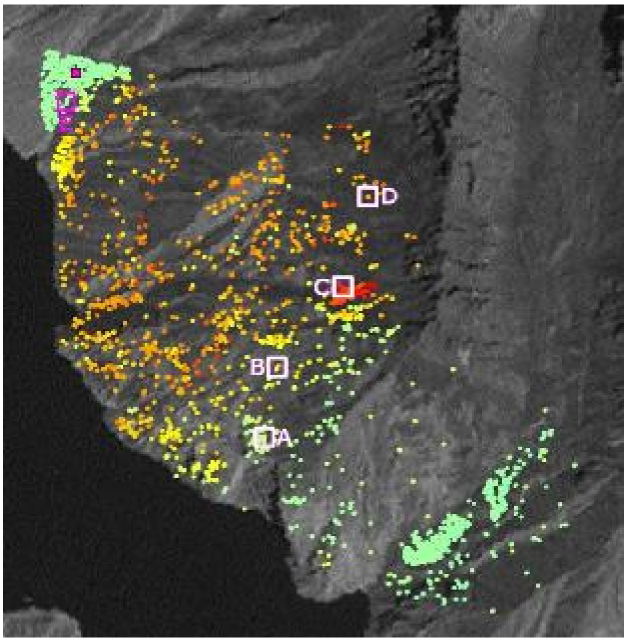
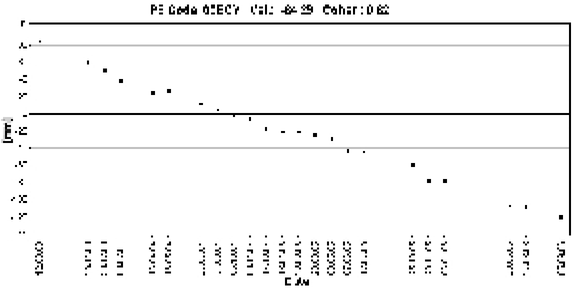
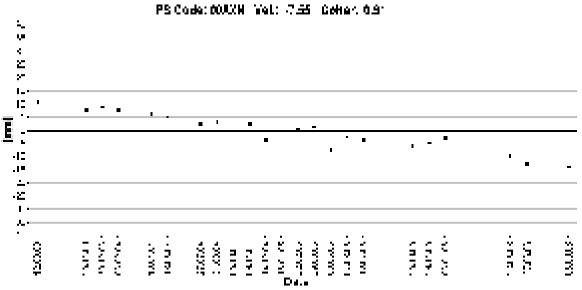


Figure 12: Location of the PS for which the time vs motion series are shown in the next figure

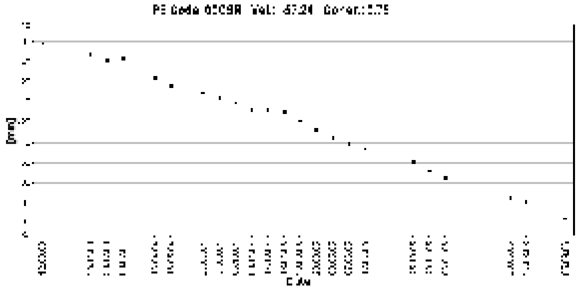


Permanent Scatterer C

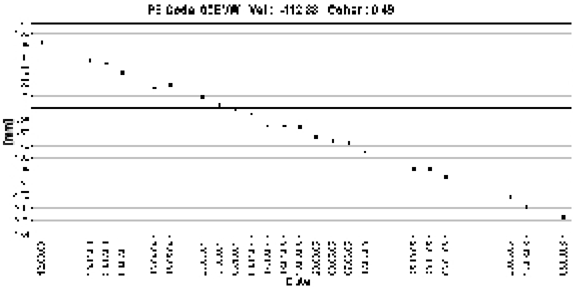


Permanent Scatterer D

Figure 13: Time vs motion series for the PS shown in Figure 12



Permanent Scatterer A



Permanent Scatterer B

6. COMPARING GPS AND INSAR RESULTS

The InSAR analysis was conducted at the very end of the overall project, with no time for an in-depth comparison of the two data sets. However, a preliminary comparison was performed for the purpose of this paper.

The displacement and velocity measurements of PS are measured along the 'line-of-sight' of the radar beam. Accordingly, these measurements have vertical, horizontal and 'down-the-slope' components. They are measurements of movement relative to a reference point deemed to be motionless, as shown in Figure 10. GPS measurements record a point's position in x, y and z coordinates. This difference in characterization means that direct comparisons between the two sets of data are more challenging whenever a PS does not correspond to a GPS station, as was the case for the RBS.

The approach to comparing the two data sets involved re-configuring the GPS data to the line-of-sight geometry of the PS data.

Figure 14 shows the reconfigured velocity data of each of the GPS stations located on the RBS. The colour of each GPS site corresponds to the average velocity reconfigured to the InSAR parameters. By comparing the the colour of the GPS points with that of adjacent PS positions, it can be seen that conformity between them is strong.

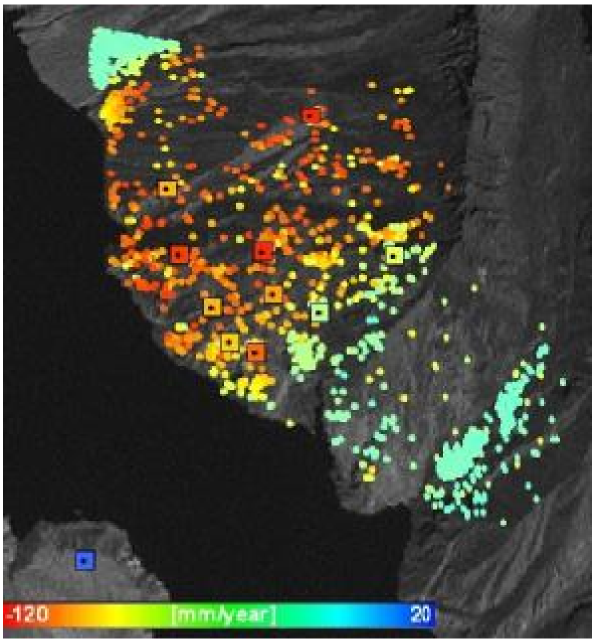


Figure 14 : Reconfigured GPS velocity data superimposed on the PS estimated average velocity

Figure 15 shows, the re-configured GPS data for site R06 superimposed on the time series for PS 00CUW located within 50 m of the GPS station. Despite the limited amount of GPS data, there is consistency in both individual displacement and displacement velocities between the two sets of data.

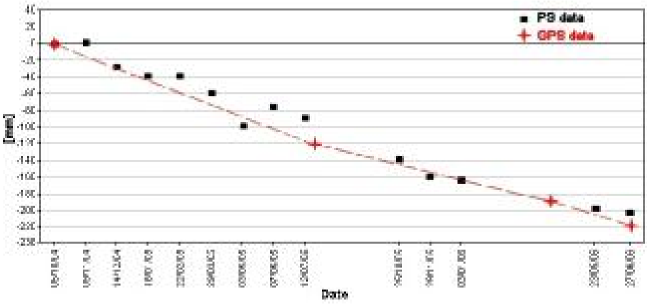


Figure 15**:** GPS data for site R06 superimposed on the time series for PS 00CUW

In addition to comparing the degree of movement at known control points (GPS stations), InSAR was also able to:

- provide a relatively dense random spatial distribution of PS across the study area;
- generate a history of movement prior to the installation of GPS stations; and
- define the boundaries of the area in motion.

7. CONCLUSIONS

The combination of terrestrial and spatial measurement was demonstrated as being a powerful means of assessing the extent of an unstable slope as well as its activity. While caution needs to be exercised in making direct comparisons between the two sets of results, they both contribute to a better knowledge of the behavior of such geohazards and therefore are part of the decision process. Furthermore InSAR has the capacity to provide valuable information on the behavior of an area under study before any terrestrial measurement systems have been installed, provided data archives are available.

The results from the geological modeling of the RBS, together with those from the GPS and PS data, suggest that the detection of surface movement does not appear to be an indication of global instability.

8. ACKNOWLEDGEMENTS

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