Polish Geological Institute Special Papers, 15 (2004): 43–52
Proceedings of the Conference "Risks caused by the geodynamic phenomena in Europe"

GROUND SURFACE CHANGES DETECTABLE BY EARTH OBSERVATION AND THEIR IMPACT ON THE STABILITY OF SLOPES

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Abstract. Uses of Earth Observation (EO) in landslide investigations are reviewed followed by discussion of their causal factors and types of slope deformation. Secondary surface indicators of changes to limit equilibrium are described and their impacts on factors of safety and deformation in different classes of geotechnical materials are tabulated for use as an input to hazard mapping.

Key words: surface change, landslides, slope stability, deformation, EO, SAR interferometry.

Abstrakt. Artykuł przedstawia zastosowania teledetekcji satelitarnej (EO) w badaniu osuwisk egzaminując główne przyczyny ruchów osuwiskowych i typy deformacji stoków. Wprowadzono koncepcję pośrednich indykatorów rozpoznawalnych na powierzchni Ziemi i wskazujących na zmiany granicy równowagi stoków. Wpływ tych zmian na współczynnik bezpieczeństwa i na deformacje stoków jest analizowany z uwzględnieniem różnych klas materiałów geotechnicznych. Wyniki są przedstawione syntetycznie w formie tabeli, wskazującej ich zastosowanie do kartowania stopnia zagrożenia osuwiskowego.

Słowa kluczowe: zmiany powierzchni ziemi, osuwiska, stabliność stoków, deformacje, EO, interferometria SAR.

INTRODUCTION AND BACKGROUND

In a previous paper (Wasowski, Gostelow, 1999), three main uses of EO satellite data in landslide investigations were distinguished:

1. Surface characterisation, i.e. initial topographical and geomorphological classification, DEMs, photogrammetry (e.g. using Ikonos, Quickbird, Spot and Landsat).
2. Measurement of ground deformation by means of SAR interferometry.
3. Systematic monitoring of slide producing agents.

Here, we explore themes two and three by developing a methodology whereby temporal ground surface changes detectable by EO might be used as an input to landslide hazard mapping.

GENERAL

The limit equilbrium of slopes is commonly expressed in terms of an engineering factor of safety *F*, where,

$$F = \frac{\text{avarage shear strength (s)}}{\text{avarage shear stress}}$$

When *F* is equal to 1.0, an average shear stress is equal to an average shear strength and a slope is at a point of shear failure for a landslide to occur there must be: an increase in the average shear stresses, for example through erosion, earthquakes, man-made changes, and/or a decrease in average shear strength (s).

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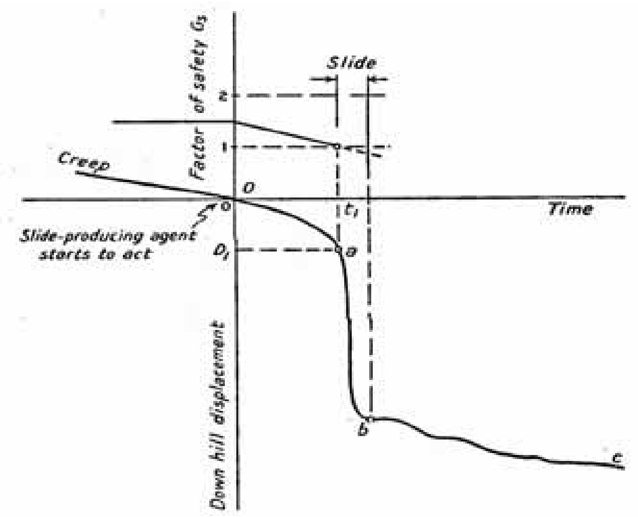


Fig. 1. Diagram showing factor of safety changes and slip surface movements preceeding, during and after a landslide (after Terzaghi, 1950)

Changes in shear stress and/or effective strengths which precede landsliding were referred to as slide producing agents by Terzaghi (1950), but are also known as causative and triggering mechanisms (e.g. Cruden, Varnes, 1996 and references therein).

It is well established that some deformations usually precede slope failure, i.e. when F = 1.0. Figure 1 (after Terzaghi, 1950) illustrates diagrammatically how in a susceptible slope, which he considered, had an initial F ≈ 1.5, the downhill displacement D, time t, and F depend on the introduction of a final slide producing agent or trigger.

Figure 1 also suggests that if the basic distribution of susceptible natural slopes are already known, then there may be two obvious EO techniques of providing warnings of impending slope failure, i.e. by:

— monitoring the causal factors and or,

— detecting and measuring slope deformation.

Such data collected cumulatively may be used to warn of trends towards instability and of failure from triggering events such as earthquakes or rainfall. It is unlikely that the timing of mass-movements can be forecast. Nevertheless, with improved resolutions and further refinements of change data, especially ground movements now detectable by EO, it is likely that greater reliance may eventually be placed on failure predictions for individual slopes.

CAUSAL FACTORS

Typical secondary indicators of landslide causal factors which might be detected through EO fall under three broad headings:

1. Alterations to the geometry or surface topography of slopes either by natural processes or man, e.g.: through river erosion, subsidence (ie subsurface erosion, karst collapse, fault movements, oil, mineral and/or water extraction, cut and fill, urban and individual building developments, quarrying). These changes principally alter shear stresses.

2. Alterations to the interaction between the atmosphere and earth surface by natural processes or man, e.g. changes to the soil/water balance and hydrogeology through precipitation, infiltration, surface evaporation, flooding and runoff; through landuse or long-term climatic change. In addition, anthropogenic effects include river regulation, hydraulic engineering works, such as: reservoirs, urban, rural water supply, irrigation and artificial recharge. These changes may affect water pressures and hence the effective strengths of materials within slopes, either increasing or decreasing stability (F).

3. Alterations to the mechanical properties of slope forming materials, e.g. through deformations caused by earthquakes, by long-term weathering processes, through interference by man — most notably through agricultural activities such as: ploughing, changing crop usage, deforestation and geochemical alterations. These changes alter the intrinsic hydraulic and strength components of both rocks and soils, most easily quantified through permeability and angles of internal friction and cohesion. It is possible for increases and decreases of these parameters values to occur.

SLOPE DEFORMATION

Deformation on slopes may arise from a wide variety of causes. Subsurface alterations to ambient stresses, by geomorphological processes, civil engineering, mining, mineral/fluid extraction or neotectonics (earthquakes) might result in surface strains. However, landslide case records have repeatedly suggested that the most significant temporal impacts have often been those related to climatic variations and their control on hydrogeology, groundwater pressures and effective strengths. The magnitudes and timing of deformations arising from such changes will depend on the hydro-geotechnical characteristics of slope forming materials which might range from engineering rocks to soils or a combination of both.

Average water tables in rock slopes depend on climate and their structurally controlled hydraulic characteristics, but are often at some depth below the ground surface. Of importance with regard to slope instability are outcrops of confined aquifers and valley or coastal landforms underlain by unconfined groundwater rock aquifers consisting of poor water bearing materials with both high mass (fracture) hydraulic conductivity and low groundwater storage. These may both be subjected to sudden and high water level fluctuations and thus effective stress changes after intense precipitation. In extreme cases, localised water level increases of up to 89 m in a 24 hour period have been recorded in some karstic limestones, which often act as landslide caprocks (Milanovich, 1976). However, despite considerable changes in mass effective strengths within such aquifers, the associated temporal surface slope deformations in such geological conditions and in many other rock types remain unknown.

In contrast, porous engineering soil materials on slopes have been studied and monitored in more detail. Secondary structures, e.g. fissures and pipes, can influence hydrogeological response and deformation in some materials, especially residual soils but generally fluctuations of shallow unconfined groundwater tables are perhaps of 0.5–3 m or so under temperate climatic conditions with average depths generally lower than in rock slopes. As a result of their lower stiffness and permeability, small, delayed seasonal consolidation and/or swelling volumetric strains occur within soils. The magnitudes detectable at the ground surface generally depend on variations in soil profile stiffness. On slopes, resultant movements over time might be found to be in a downslope direction but such deformations might not necessarily always reflect shear movements or movements leading to shear failure. For example, using slope indicators Eigenbrod (1993) measured annual rates of surface movement of up to 50 mm per year on a 7 degree natural slope cut in soft peri-glacial silty clays in Canada and found them decreased to zero at 2 m depth. Laboratory investigation confirmed that the movements described as "creep" were chiefly due to seasonal pore water pressures. A shear surface was not found and limit equilibrium stability analyses indicated that slope was stable.

Ng *et al* (2003) similarly described a well instrumented 11 m high 22 degree cut-slope in medium plasticity swelling clay in China. There, downslope surface displacements of 12 mm were recorded after single artificial rainfall events, decreasing to zero at about 6 m. Vertical swelling of the bare (unvegetated) cut slope surface of up to 30 mm took place at the same time.

Tavenas and Leroueil (1980) provided laboratory and field evidence that as a slope approached failure, the downslope deformation or strain rate increased. It has also been confirmed by field case records in both rocks and soils that accelerating strain rates do occur prior to shear failure during research investigation of first-time landslides, but without appropriate and costly field instrumentation, it is doubtful that such strains will be detected routinely, especially in wide-area investigations. Notwithstanding this limitation, it is suggested here that the detection of any form of temporal wide-area surface strain is an important contribution to slope stability studies. EO using SAR interferometric techniques (e.g. Wasowski, Singhroy, 2003) have recently provided promising results showing ground surface deformation changes over time on landslide susceptible slopes, but as briefly outlined above, the parameter and geological boundary uncertainties which control them need to be investigated and better understood before they can be confidently used directly for predicting (warning) of potential instabilities. Further research is certainly needed using the technique on test areas with different geological and geomorphological scenarios, but nevertheless, it is still possible at present to make some broad preliminary statements regarding EO surface changes and their potential impacts on factors of safety and subsequent landslide deformations.

EO, SURFACE CHANGES AND THEIR IMPACTS ON FACTORS OF SAFETY AND DEFORMATION

Table 1 summarises the surface features (including deformation) which might be detected by EO and attempts to rank them qualitatively with respect to their potential impact to factors of safety (F) and where failure occurs, to subsequent deformations. This is based on a qualitative assessment of (a) their impact on limit equilibrium, i.e. to shear stresses or shear strengths on slopes "close" to a factor of safety of 1.0 and (b) general stress-strain characteristics. Such slopes would have been identified through pre-existing general knowledge of topography (slope angle), geotechnical material class, regional hydrogeology and climate. Impacts might be positive or negative, depending on the types of change and their location on a natural slope, and this is indicated on Table 1.

GROUND SURFACE CHANGES AND GEOTECHNICAL MATERIAL CLASSES

The generally accepted unified soils classification (USC) includes 15 engineering groups and is based on consistency (plasticity) and particle size grading. Table 1 simplifies the USC into 6 cohesive and cohesionless groups and because potential deformation following surface change is of interest, uses broad stress-strain characteristics (geo-mechanical brittleness) to distinguish between the groups. A single, highly organic class (essentially peat) is also retained for completeness.

It is recognised that there are a great variety of igneous, metamorphic and sedimentary engineering rock types with varying levels of intrinsic strength and rock-mass geotechnical behaviour. However, for EO slope change detection purposes it is suggested that it might often be sufficient to firstly recognise and map engineering soil and engineering rock outcrops separately, as the former are likely to have been subjected to most vegetation and anthropogenic alteration.

In common with the engineering soil groups, it is the hydrogeological flow systems of rock slopes, combined with their overall structure, fracture frequency (faults and joints), frictional strengths, orientation and connectivity together with slope angle which generally control shear strengths and slope stability. In most cases the information required, especially at the scales necessary to make analytical judgements, will be poorly known. In the scheme presented here which places em-

Table 1

Surface changes and their impacts on factors of safety and deformation

Principle change to slope equilibrium	Surface change detection on slopes using integrated EO sources	Potential impact to factor of safety (F)	Potential landslide magnitude*	Potential landslide spatial frequency	Potential failure displacements – first-time slides in engineering cohesive, cohesionless and organic soils on susceptible slopes**					Potential displacements - Reactivated cohesive soil slides		First-time slides in structured soils (soft rocks), rockslides and falls	
					brittle drained soil stress-strain behaviour	non-brittle drained soil stress-strain behaviour	compact or dense cohesionless soils	loose or metastable cohesionless soils	organic soils	brittle materials (high plasticity soils)	non-brittle materials (low plasticity soils)	high discontinuity frequency and connectivity	low discontinuity frequency and connectivity
Shear stresses	imposed loads through urban centres/major landscaping on slopes	(+) to (-)	high to low	low	high	low	low	high	high	high to low	low	high to low	low
Shear stresses	imposed loads through individual buildings or other isolated man-made structures	(+) to (-)	high to low	low	high	low	low	high	high	high to low	low	high to low	low
Shear stresses	individual geometrical slope toe changes (eg engineering road cuts, river, coastal erosion)	(-)	high	low	high	low	low	high	high	high to low	low	high	low
Shear stresses	individual geometrical slope crest changes (fills, embankments)	(-)	high	low	high	low	low	high	high	high to low	low	high to low	low
Shear stresses	individual geometrical changes to the slope profile (cuts and fills ie buildings, roads)	(+) to (-)	high to low	high to low	high	low	low	high to low	high	high to low	low	high	low
Normal effective stresses and thus frictional strengths (ϕ’)	soil water balance (natural vegetation changes, wild-fires, agricultural changes, pavement construction)	(+) to (-)	low	high	high	low	high	high	high	low	low	high	v. low
Cohesive components of effective strengths (c’)	surface physico-chemical changes to soils and/or weathered rocks (eg, through deep ploughing),	(-)	low	high	high	low	low	high to low	high	low	low	low	low

Principle change to slope equilibrium	Surface change detection on slopes using integrated EO sources	Potential impact to factor of safety (F)	Potential landslide magnitude*	Potential landslide spatial frequency	Potential failure displacements – first-time slides in engineering cohesive, cohesionless and organic soils on susceptible slopes**					Potential displacements - Reactivated cohesive soil slides		First-time slides in structured soils (soft rocks), rockslides and falls	
					brittle drained soil stress-strain behaviour	non-brittle drained soil stress-strain behaviour	compact or dense cohesionless soils	loose or metastable cohesionless soils	organic soils	brittle materials (high plasticity soils)	non-brittle materials (low plasticity soils)	high discontinuity frequency and connectivity	low discontinuity frequency and connectivity
Shear stresses (erosion) and normal effective stresses/frictional strengths (long-term groundwater rise)	flooding in river valleys. Construction of man-made reservoirs	(-)	high to low	high to low	high	low	high	high	high	low	low	high	low
c’ and ϕ’	accelerating uni-directional downslope displacement/ deformation	(-)	high to low	high to low	high	high	high	high	high	high	low	high	high
c’ and ϕ’	random low magnitude surface deformation/ seasonal volumetric changes	(+) to (-)	low	v. low	low	v. low	v. low	low	low	low	v. low	high	high
c’ and ϕ’	random but high magnitude surface deformation/seasonal volumetric changes	(-)	high	high to low	high	low	high	high	high	high	high	high	high

* High magnitude: large, individual deep-seated landslides (e.g. with a volume greater than 250,000 m^3); low magnitude: small predominantly shallow landslides (e.g. with a volume less than 50,000 m^3)

** Susceptible slopes, i.e. close to limiting equilbrium phasis on unfavourable geotechnical surface changes on a slope, only two simple rock classes are used. The first includes steep susceptible slopes on massive outcrops where fracture frequency would normally be low. These might include mainly igneous and some metamorphic rock types. The second class includes rocks where fracture frequency and connectivity (encouraging localised effective stress changes) might be higher. In a very general sense this will thus include most sedimentary and some metamorphic rock types.

Preliminary groupings of eleven surface changes which might be detectable by EO have been identified and their relative geotechnical impacts on post-failure displacements have been qualitatively assessed in relation to the general limit equilibrium model and the nine geotechnical material classes.

GROUND SURFACE CHANGE AND DEFORMATION

GENERAL

Precursory and post-failure slope deformations may be responses to limit equilibrium changes, and might be detectable through EO as a surface change. However, at present there is uncertainty concerning the magnitudes and time signatures of temporal wide area ground movements and associated indicators in different engineering soil and rock environments. Until there is a better understanding, a tentative grouping of just three classes is shown in Table 1.

Uni-directional deformation infers a constant or accelerating temporal rate of down-slope displacement. In a wide area study, they are likely to reflect shear strains on active landslides and hence might be of limited areal extent or not present. The remaining two groups divide temporal deformations into low and high magnitude “random” surface deformations, i.e. where there are no obvious directional trends. These surface movements, where truly reflecting slope ground strains are likely to be chiefly volumetric, but other factors such as neo-tectonism and anthropogenic influences might also be significant in some circumstances.

Despite the uncertainty with the interpretation of wide-area temporal ground strain signatures it would seem that where there is evidence for both cause and effect, i.e. to stresses, effective strengths and deformation, that such slopes could be considered more susceptible to instability than others. The most promising SAR interferometric technique which is able to provide time series of surface deformations and thus a possibility of distinguishing or classifying different, wide-area geological behaviour is called Permanent Scatter (PS).

EXAMPLES OF SLOPE SURFACE DEFORMATION TRENDS DETECTED BY SATELLITE SYNTHETIC APERTURE RADAR(SAR) INTERFEROMETRY

The Permanent Scatterers (PS) technique developed at Politecnico di Milano, Italy (Ferretti *et al*., 2000, 2001; Colesanti *et al*., 2003) overcomes several limitations of conventional SAR differential interferometry (DInSAR) applications in slope instability studies. It is capable of generating high precision ground displacement data and under suitable conditions, i.e. favorable slope orientations and dips with respect to the radar sensor acquisition geometry, the presence of many privileged radar targets such as buildings, and occurrence of very slow movements, the PS approach can offer a valuable alternative for providing initial wide-area assessment of ground displacements.

To provide examples of slope surface deformation trends detected by PS approach we use the case history of a large landslide in Liechtenstein (Fig. 2). The results of the PS interferometry application in

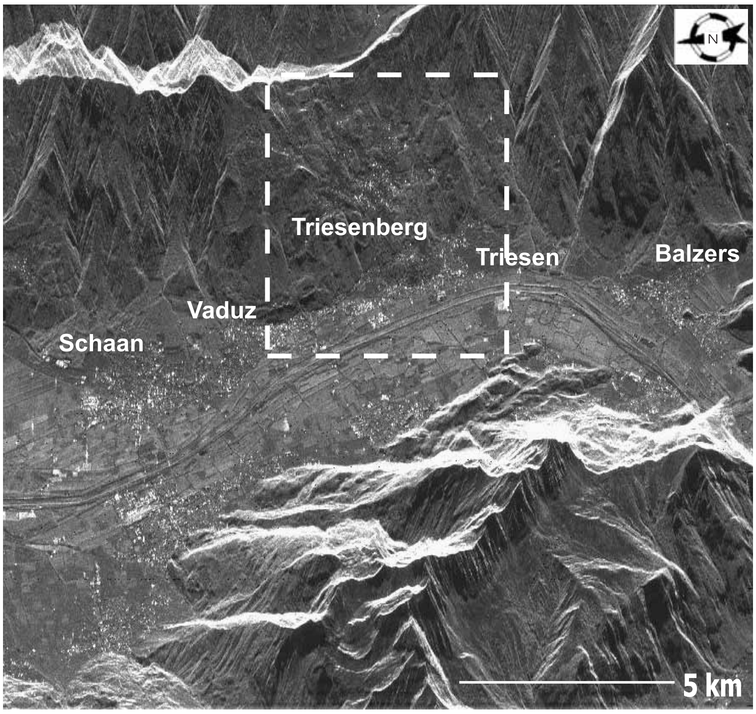


Fig. 2. Multi-image SAR reflectivity map of the Triesenberg–Triesen landslide area located in Rhine river valley Liechtenstein (after Colesanti, Wasowski, 2004, modified)

Note that high reflectivity image pixels (ligth colour) correspond mainly to man-made structures within and around the towns of the valleys, and secondarily to rock exposures; the objects whose reflectivity does not vary significantly in time (high coherence) can be used for Permanent Scaterrers (PS) analysis; the white dashed rectangle indicates the area shown in Figure 3

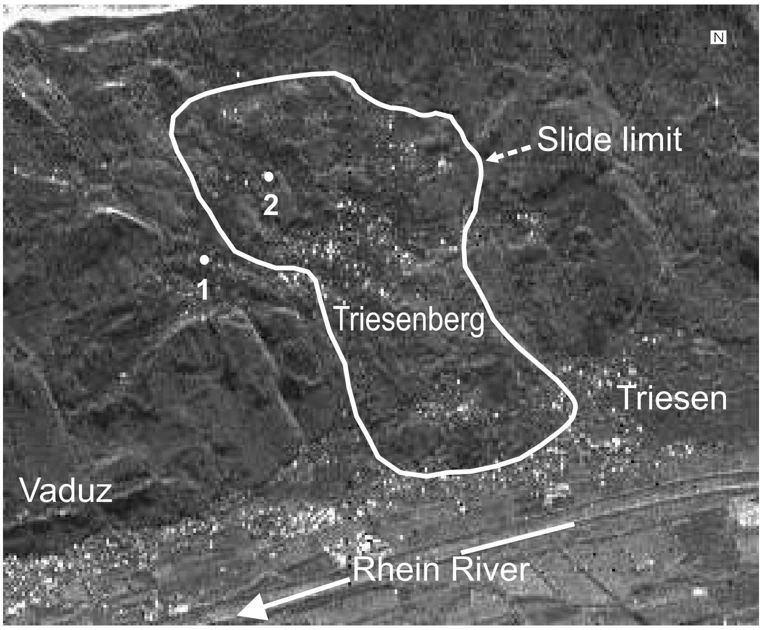


Fig. 3. SAR image showing the slope affected by the Triesenberg–Triesen landslide

White dots marked with numbers 1 and 2 indicate locations of two representative Permanent Scaterres (PS), whose radar Line of Sight (LOS) displacement time series are shown in Figure 4

this case have been recently described by Colesanti and Wasowski (2004) and here we offer only some background information.

The area of interest is located in the Liechtenstein Alps, south of the country's capital, Vaduz (Fig. 2). The Triesenberg–Triesen landslide (Allemann, 2002) occupies the west-facing slopes of the Rhine river valley which is characterised by high local relief (over 1000 m). The two main towns affected by landsliding are Triesen and Triesenberg (Fig. 3), located respectively at about 500 and 900 m a.s.l.

A total of 38 images from the European Space Agency satellite ERS which covered the time span August 1992 – August 2001 were analysed. The monitoring of the Triesenberg–Triesen landslide by PS interferometry suggested that at present one of the most attractive and proven contributions provided by this remote sensing technique lies in the possibility of wide-area qualitative distinctions between geologically unstable and stable areas (Colesanti and Wasowski, 2004). The distinction is based on the identification of slope segments characterised by the presence or absence of down-slope ground surface deformations.

Figure 4 shows examples of time series of the displacements occurring along the satellite sensor-target line of sight (LOS) for PS 1 and PS 2 situated, respectively, outside and within the Triesenberg–Triesen landslide. As expected, PS 1, which is located on a stable rock outcrop indicates a nearly zero LOS motion; i.e. –0.36 mm/yr, a value is within the precision error which ranges typically from 0.1 to 0.5 mm/yr (Colesanti *et al*., 2003). PS 1 time series indicates also that despite the rock outcrop appears to be stable, the results of LOS measurements are dispersed in general by up to ±5 mm around the 0 value. This may be viewed as "noise" in the measurement data. Indeed, the precision of each single LOS measurement ranges between 1 and a few mm (e.g. Ferretti *et al*., 2000, 2001).

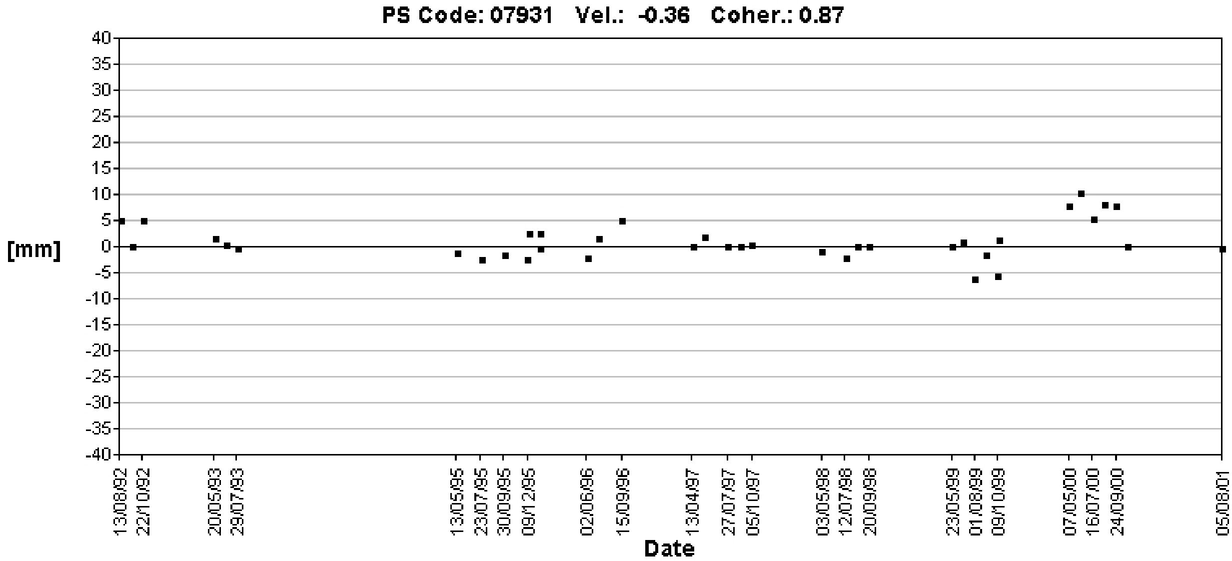
PS 2 corresponds to railings which are present along a road crossing the upper part of the Triesenberg–Triesen landslide (Fig. 3). Its time series reveals a more or less linear or constant trend of downslope displacements (Fig. 4). This is an example of what can be termed an uni-directional downslope deformation (cf. Table 1).

Clear examples of "random" slope surface deformations where there are no obvious directional trends appear unavailable at present. Indeed, given the current operational constraints of satellite radar systems (in particular the operating frequency and the relatively long revisiting time), it is now possible to monitor with confidence only very slow ground motions (on the order of several cm/year). This and the millimetric errors affecting each single LOS radar measurement imply that it might be difficult to distinguish between the effects of noise in the data and the random deformations possibly linked to seasonal changes in slope ground strains. Such difficulties may be more apparent in cases of low magnitude volumetric changes, for example in stiff soils and rocks.

It is suggested that ground control and truthing may always be needed in wide-area investigations because, in addition to mass movement processes, other deformation phenomena may have to be taken into account to interpret correctly the significance of surface changes detected from SAR interferometry (cf. Wasowski *et al*., 2002). These include subsidence (whether caused by natural processes such as compaction, thawing, or man-made), settlement of engineering structures, and shrink and swell of some geological materials.

LANDSLIDE MAGNITUDE

Anthropogenic changes on slopes detectable by EO generally fall into three broad types: point (e.g. a building, etc.), line (e.g. a road, utility, pipeline etc) or areal (agricultural, urban centres, mineral extraction etc). The scale of such impacts thus have significance with respect to potential landslide magnitude and frequency with respect to the different geotechnical classes present on slopes and this is also indicated on the Table 1.



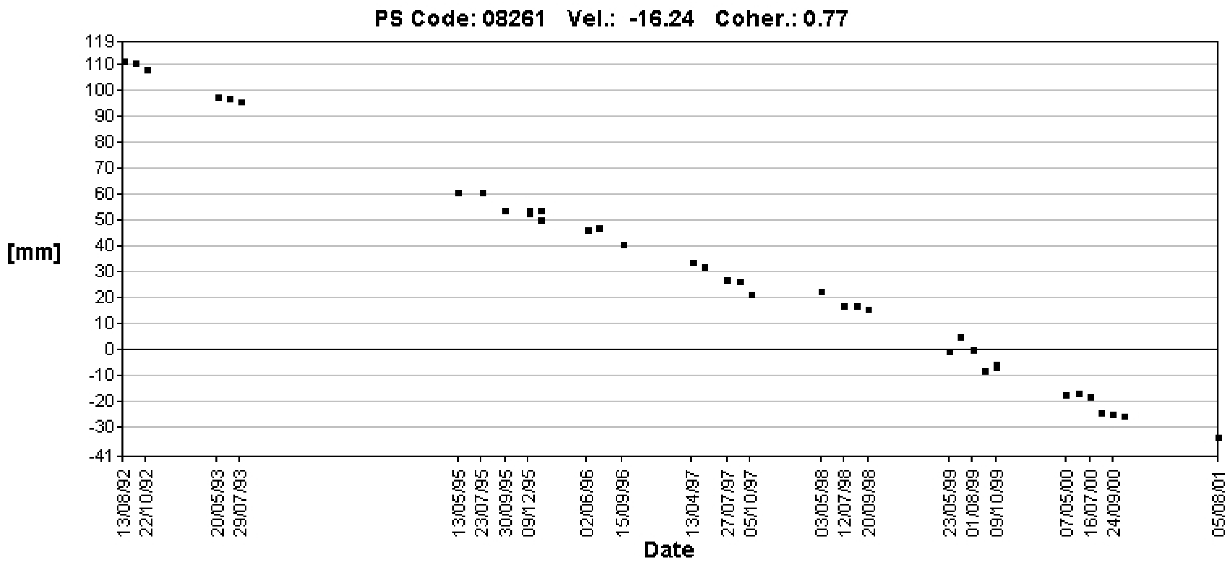


Fig. 4. LOS displacement time series of PS 1 (upper graph) and PS 2 (lower graph) situated, respectively, outside and within the Triesenberg–Triesen landslide (see Figure 3 for location)

Vel. stands for average annual velocity (mm/yr); negative sign indicates displacements away from radar sensor (in this case downslope, given desceding acquisition geometry and west facing direction of the area of interest); Coher. Stands for coherence; black squares indicate the result of each single LOS measurement

"SLOPE FATIGUE" AND POTENTIAL WARNING OF INSTABILITY USING EO

All natural slopes have been subjected to geological and historic change and as a result factors of safety would have also varied over time (Terzaghi, 1950). It is suggested here that slopes susceptible to instability which have or are being subjected to the greatest frequency and magnitude (+ to -) of factor of safety changes from ambient and alternating stresses or intrinsic strength changes might be described as being more "fatigued" than others and hence they may have greater probabilities that FS will reach 1.0. Secondary surface indicators of past and current factor of safety changes which help to identify such slopes can be obtained with the continued development and introduction of integrated EO techniques.

The numerical changes to factors of safety will generally be unknown, but in most cases it is likely that results from EO will suggest very small percentage decreases or increases and hence it will not be possible to quantify hazard or risk directly. Nevertheless, when using integrated EO in surveys of natural hazard it is perhaps possible, at present, to identify and thus focus upon 4 broad groups of situations where a significant geotechnical impact involving cause and effect has occurred. These provide

4 separate general warning levels of interest to a geologist, engineer or planner.

A. EO Detection:
Uni-directional rates of downslope displacement.
Warning level:
Pre-cursory slope movements, creep, (first-time failure) or active landslide.

B. EO Detection:
1. Point load or unload on slopes susceptible to instability, with no deformation record.
2. Line load or unload on slopes susceptible to instability, with no deformation record.
3. Areal vegetation change on slopes susceptible to instability, with no deformation record.
Warning levels:
Evidence for positive or negative changes to limit equilibrium of a slope.

C. EO Detection:
1, 2 and 3 in B plus evidence for temporal high frequency and/or magnitude ground surface deformation.
Warning level:
Evidence for changes to the limit equilibrium of a slope in an unstable hydrogeological regime, i.e. where there is a potentially a large natural fluctuation in factor of safety.

D. EO Detection:
1, 2 and 3 in B plus evidence for temporal low frequency and/or magnitude ground surface deformation.
Warning level:
Evidence for changes to the limit equilibrium of a slope in a comparatively stable hydrogeological regime, i.e. where there is small natural fluctuation in factor of safety.

Acknowledgments. The authors would like to acknowledge financial support from the EU Framework V R&D programmes under project EVG1-2001-00067 “LEWIS”. JW thanks Dr. C. Colesanti, Dr. A. Ferretti, Prof. C. Prati and Prof. F. Rocca of the Politecnico di Milano (POLIMI), as well as the T.R.E. staff of Milan, for helpful discussions on SAR interferometry. The PS analysis of the Triesenberg–Triesen landslide was performed by POLIMI in the framework of the EC project MUSCL (EVG1-CT-1999-0008), coordinated by Prof. H. Rott (IMGI Universität Innsbruck).

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