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A GIS MODEL FOR INTEGRATING TEMPORAL GROUND SURFACE CHANGE WITH POTENTIAL SLOPE INSTABILITY USING EO: A CASE STUDY FROM THE CARAMANICO AREA, ABRUZZO, ITALY

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Abstract. This paper describes a new methodology for assessing landslide susceptibility from temporal land-use change using integrated earth observation (EO) and a GIS. Ground surface change data using LANDSAT and INSAR (permanent scatterer, PS) are used in a physically based geotechnical model which firstly defines initial susceptibility to landslides through geological and geomorphological background data or field study. Secondly it provides the impacts of change in terms of positive or negative effects on limit equilibrium factors of safety (FS) and thirdly the potential outcome of changes at a FS of 1.0 in terms of slope deformation. Application of the model in the Caramanico area using EO data from 1987 to 2000 is described and interpretative and image processing procedural difficulties are discussed. In this study only surface changes from vegetation to artificial structures could be reliably used in the model. Nevertheless preliminary results show promise, suggesting there may be some spatial relationships between areas of historic surface change and deformation recorded by GPS and PS in the urban area.

Key words: geotechnical model, slope deformation, landslide susceptibility.

Abstrakt. W artykule przedstawiono nową metodę oceny podatności osuwisk na okresowe zmiany użytkowania terenu. W badaniach wykorzystano zintegrowane obserwacje satelitarne oraz technikę GIS. Na podstawie informacji o zmianach powierzchni Ziemi, uzyskanych z satelitów LANDSAT i INSAR, opracowano model geotechniczny, który, po pierwsze, na podstawie danych geologicznych i geomorfologicznych lub też bezpośrednich badań terenowych, określa podatność terenu na powstawanie osuwisk, po drugie, wskazuje wpływ zmian na granice równowagi czynników bezpieczeństwa (FS), a po trzecie, przedstawia potencjalny efekt zmian na deformację zboczy przy współczynniku FS = 1.0. Opisano też wykorzystanie tego modelu w rejonie Caramanico (Włochy) z uwzględnieniem obserwacji satelitarnych z lat 1987–2000. Przedyskutowano trudności pojawiające się w trakcie obróbki danych satelitarnych i podczas ich interpretacji. Okazało się, że w opracowaniu dotyczącym rejonu Caramanico można wykorzystać jedynie dane dotyczące zmian powierzchniowych, związanych z zamianą terenów pokrytych roślinnością na tereny zabudowane. Niemniej, wstępne wyniki wspomnianych badań sugerują, że mogą istnieć przestrzenne związki istniejących uprzednio zmian powierzchni z deformacjami obszarów zurbanizowanych, odnotowanymi przez pomiary GPS oraz przez satelitarne pomiary radarowe PS.

Słowa kluczowe: model geotechniczny, deformacje zboczy, podatność na osuwiska.

INTRODUCTION

Landslide hazard can be described as the magnitude and probability of downslope ground displacements (Fell, 1994). The physical controlling factors are comparatively well known and there have been several attempts to empirically weight different combinations for mapping mass movement susceptibility and magnitude (e.g. Leighton, 1976; Brabb, 1984; Lewis, Rice, 1990; Siddle *et al*., 1991; Carrara *et al*., 1991; Mejia-Navarro, Wohl, 1994). Nevertheless, while some success has been claimed, difficulties have arisen with choosing appropriate map scales, selecting which factors to include, consistently weight-

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ing them, taking into account temporal changes and obtaining field data in a cost-effective manner.

A second problem for defining hazard, rather than susceptibility to hazard is calculating the probability of landslide occurrence. There are rarely sufficient historical deformation records or data for obtaining triggering thresholds and if ground conditions change between landslide events, any thresholds may themselves have changed also, especially if there has been man-made interference.

An alternative approach to "factor weighting" has adopted deterministic physical models. For example, Montgomery *et al.* (1998) used a GIS coupled with hydrological and infinite slope analysis for modelling factors of safety (FS) at 1:200,000 scale and Miller (1995) also used a GIS with a circular limit equilbrium slope stability analysis to produce FS maps at 1:24,000 scale. An advantage of using such models is the ability to choose failure mechanisms for individual slopes, although there are obvious problems in obtaining appropriate input data over large areas.

REGIONAL SLOPE INSTABILITY, TEMPORAL GROUND SURFACE CHANGE AND EARTH OBSERVATION (EO)

Slope movements start to occur when limit equilibrium factors of safety (FS) of slipped masses, or potential first-time failures approach 1.0. They become time dependent when natural geomorphological processes and land-use changes alter shear stresses and effective shear strengths and hence a FS. Difficulties in predicting future instabilities arise when attempting to discover where such changes have taken place and their exact nature and frequency. For example, in some situations a series of small, historical natural or artificial changes may have improved a FS, whilst in others the opposite may have occurred.

Montgomery *et al.* (1998) discussed the effects of such changes in the context of erosion and shallow landslides in watershed management and concluded that "societies still generally lack effective techniques for managing the long-term influence of human interference on environmental processes". Additional case records and further research into historical geotechnical impacts from man-made change were thus considered to be important aspects of hazard assessment, particularly where affected slopes were of marginal stability.

Geotechnical impact assessments of land-use changes can be carried out using aerial photographs, maps, archival reports, research publications, etc. However, in many circumstances it can be time consuming and critical data may often be lacking. EO of historic and recent images offers clear advantages for a variety of engineering purposes and end-users. It has been routinely used to monitor agro-environmental changes, but rarely in relation to geotechnics and slope instability. In this paper we put forward a new data management procedure which uses a GIS coupled with EO and a simple geotechnical model as a means to assess ground surface impacts from historical and future land-use changes for this purpose.

A PHYSICALLY BASED, CONCEPTUAL GEOTECHNICAL MODEL

A major difficulty with choosing and applying a physically based model in regional landslide studies is the wide variety of geological parameter and boundary conditions that may be present. Slope materials may vary from very soft soils to very strong rocks, e.g. with unconfined compressive strengths of less than 0.025 MPa to over 250 MPa respectively. In addition minor geological detail such as mineralogical, structural or groundwater anomalies may often dominate strength behaviour and mass movement characteristics. Different geo-mechanical models will thus apply to different modes of slope failures and the distribution and geomorphology of the latter may be controlled by local rather than regional factors.

The most commonly used mass-movement classifications which have been used in hazard assessment have been based on morphology, often coupled with descriptive terms relating to styles of deformation (e.g. Picarelli, 2000). Landslides form one class of mass movement and to overcome the need to consider a wide variety of potential types, the conceptual model adopted here uses ground deformation as the most important and common characteristic of all gravitational mass-movement on slopes, whether they be slides, falls or flows.

SLOPE DEFORMATION AND LANDSLIDES

Leroueil (2001) distinguished 4 separate deformation stages, which might be detected in the field (but not necessarily in all mass movements), i.e.:

i) pre-failure, i.e. all deformation leading to failure, mainly arising from stress changes, creep and progressive failure;
ii) onset of failure – the formation of continuous failure surface;
iii) post-failure – the movement of a sliding mass until it stops, characterised by an increase then a decrease in velocity;
iv) reactivation stage, a slide mass moves along one or several pre-existing shears.

For first-time slides, Terzaghi (1950) linked together the effects of slide producing agents with FS, ground deformation and time (Fig. 1). He made an assumption that if a change (for our purposes a surface change) to limit slope equilibrium occurred (and for this, an arbitrary FS of less than 1.5 was chosen) then pre-failure deformation would occur, leading to a gradual

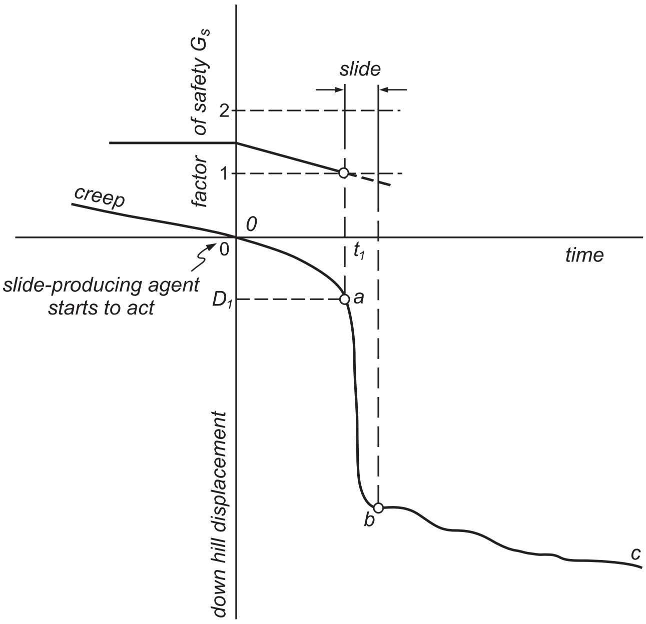

Fig. 1. Diagram showing factor of safety changes and slip surface movements preceeding, during and after a landslide (after Terzaghi, 1950)

reduction in FS over time. If and when this reached 1.0, a rapid downslope displacement would take place. The periods over which pre-failure deformations might operate were not discussed, but such strains if detectable in the field might often be described as "creep" or landslide pre-cursors, i.e. comparable to Leroueils slope deformation stages i) and ii). In Terzaghi's model the phase of rapid post-failure displacement thus corresponds to Leroueils deformation stage iii).

For reactivated slides, or first-time slope movements along continuous discontinuities formed tectonically, Picarelli (2000) suggested both pre- and post-failure deformation stages might also be identified. The first referring to strains required to overcome any viscous or shear surface roughness and the second actual reactivated (stage iv) displacements.

EO AND THE CONCEPTUAL MODEL

There are 4 main considerations and procedures which need to be built into a model that predicts FS impacts and the subsequent outcome of historical ground surface changes detected by EO:

— the identification of slopes susceptible to mass movement, i.e. close to a factor of safety of 1.0, where stress or strength changes might lead to stage i) or stage iv) deformations;
— the identification of historic and periodic ground surface changes using EO;
— the impact of those surface changes on the FS (i.e. positive or negative);
— a procedure for predicting the magnitude and impact of deformations on slopes applicable in a wide variety of different geological and geomorphological environments.

Identification of susceptible slopes

The approach adopted in this study was to use background geological and geomorphological information to establish slope angle instability thresholds for the geotechnical classes present in a study area. Such thresholds depend on landslide histories, local groundwater conditions and for intact slopes, their heights. They must be obtained independently for a study area, ideally by field investigations or by using expert opinion. Because of uncertainty, it is likely in practice that a range of values will often be adopted rather than a set of single figures.

Ground surface changes using EO

Large scale stereo aerial photographs have been widely and succesfully used in landslide investigations for several decades and are also very useful in land-use change analysis. However, the application of satellite optical imagery for land-use mapping has the additional advantage of wide-area coverage, regular re-visit times and the possibility of exploring different spectral characteristics. In this study LANDSAT imagery was used because it offered a sufficiently long time series that covered the decade of 1990 and a comparatively low cost. SPOT 5 and the new commercial satellites such as Ikonos and Quickbird offer much better ground resolution, but their archives are currently too short for historical investigations of land-use change. Nevertheless it is considered that the same methodology can be used with this newer data for monitoring future rapid change, especially in urban and peri-urban areas.

Pre-cursory and post-failure deformations might also be detectable through EO as a surface change and if uni-directional (i.e. not random) may represent temporal downslope displacements in areas where a FS is very close to, or at 1.0. We have used here only slope deformation trends detected using the method similar to the Permanent Scatterers (PS) satellite Synthetic Aperture Radar (SAR) interferometry. An innovative technique developed at the Politecnico di Milano, Italy (Ferretti *et al.*, 2000). Under suitable conditions this application has the capability of generating accurate ground displacement data on a pixel by pixel basis with a ground resolution of about 25 m.

Surface change impact to factors of safety and "slope fatigue"

Gostelow and Wasowski (2004) recognised 12 groups of ground surface changes which might be detected by EO and qualitatively summarised their impacts with respect to the limit equilibrium of slopes and FS in terms of positive or negative effects. The two sets of ground surface change data (i.e. LANDSAT and PS) can be obtained for a study area between any required periods of earth observation and their relative impacts to equilibrium can be considered either individually, or cumulatively. For the latter case, it might also be suggested that slopes with a large number of historic positive and/or negative surface changes might have greater geotechnical uncertainty than others and to draw attention to these, a concept of "slope fatigue" was put forward (*op. cit.*). With experience from additional applications of the model it may be possible to use such a concept to further sub-classify slopes with respect to hazard.

Slope deformations and material "Brittleness"

The potential outcomes of the ground surface change impacts were considered with respect to high and low slope shear deformations. Geotechnical, engineering soil classes were thus classified and mapped in terms of potential strength loss or "brittleness". Those with a high inherent brittleness were considered to have the greatest potential for strength loss and large deformations through sliding and those with a low brittleness the least. The concept was originally formalised by Bishop (1967) as a brittleness index (I_B), where:

$$I_B = (Sp - Sr)/Sp$$

and Sp and Sr are peak and residual shear strengths (under either drained or undrained conditions) respectively. The assumption has been made in the model that slopes composed of materials with the greatest potential for strength loss and large deformations are more hazardous than those where deformations are potentially limited. For example, Figure 1 illustrates the case of a brittle failure in a material where a rapid acceleration and high magnitude of deformation occurred. However, not all mass movement deformation would necessarily follow that pattern. For example, landslipped or colluvial slopes composed of high plasticity materials at residual strength will have "lost" most of their initial brittleness. Reactivated movements, although serious in some circumstances, are thus likely to be of lower magnitude and more predictable than those on intact slopes consisting of the same materials close to a FS of 1.0.

For this pilot study in Italy, a distinction was made between potential slope movements in engineering soils and rocks. The 15 engineering soil groups used in the unified soil classification (USC) were divided on the basis of stress-strain (brittleness) characteristics into 7 cohesive, cohesionless and organic classes. Only 2 rock groups were identified, divided on the basis of discontinuity levels. Each of the 9 groups was assigned a qualitative high to low level of potential deformation, which might occur (at FS close to 1.0) following the introduction of a land-use change which might act as a slide producing agent (Gostelow, Wasowski, 2004).

THE CARAMANICO STUDY AREA

Caramanico is a small but important thermal-spa hill-top centre and holiday resort located in the Abruzzi region (central Italy) (Fig. 2). The surrounding valley slopes have been characterised by a long record of historical landslides typical of mountainous settings subjected to relatively high average precipitation and seismic activity. Furthermore, there are indications that 20th century human alterations to the local environment and poorly planned construction have resulted in an increase of landslide activity and damage (Wasowski, 1998).

It is possible to recognise three broad groups of mass movements affecting the area, i.e.:

— reactivation of ancient colluvial soil deposits, which have arisen from Quaternary valley side slope development;

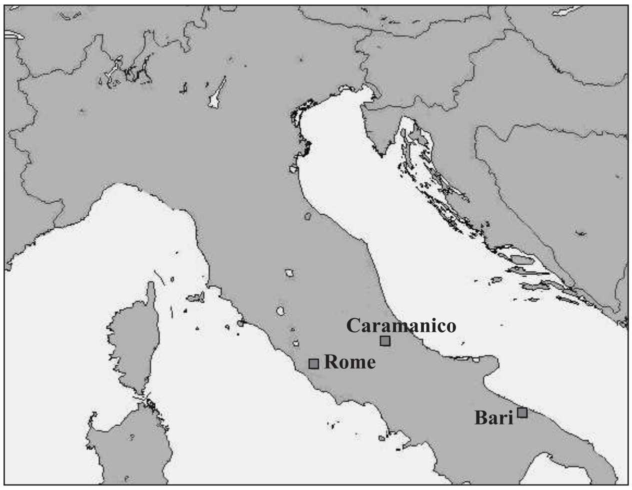

Fig. 2. Location of the Caramanico study area

— surficial degradation of steep mudstone slopes currently undercut by the Orta river (including both reactivated and first time movements);

— rockfalls.

Figures 3 and 4 shows the general setting of the town and the surficial degradation of slopes next to the Orta river.

The environmental factors controlling slope instability have been reviewed by Wasowski and Del Gaudio (2000) and are not discussed again in detail here. However, its unfavourable hydrogeological setting, which includes a hilltop aquifer (limestone megabreccia) and thick, widespread medium to low hydraulic conductivity colluvium overlying a mudstone aquiclude, provides a geological setting favourable to slope instability. A high local relief, steep slopes, gully erosion and strong river downcutting are the main geomorphological factors also encouraging mass-movements. Landslide triggers are related to climatic, human and seismic causative factors, but most of the recent cases have all followed several days of high precipitation.

Given the variable nature of the litho-stratigraphy and groundwater conditions of the landslipped areas, it has been difficult to estimate effective shear strengths and FS for engineering design, despite the considerable number of borehole and piezometric records that are available.

Prior to the use of EO, a comparison of geo-referenced, ortho-rectified air-photos from 1954 and a one-metre resolution orthophoto image from 1997 were analysed with respect to land-use change in the Caramanico area. The classification results showed a decrease in cultivated land (from 63 to 15%, expressed as area frequency) linked to abandonment of agricultural activity. This coincided with large increases of grassland (17.5 to 38.5%) and arboreous land (8.5 to 35%) as well as expansion of settlements and infrastructure (1 to 4%). In general, although regional landslide inventories are not available for this period there is evidence of a decreased landslide activity in rural areas as a result of the growth in forested areas and an increase in activity in the urban and peri-urban areas. This region and urban centre was thus chosen as a test area for investigating the application of the conceptual model using periodic EO change data.

Fig. 3. General view of Caramanico and the Orta valley test area

The town of Caramanico is in the middle and the hillslopes most prone to landsliding (white arrow) are to the right of centre

Fig. 4. Widespread, mostly shallow mass movements on May 1991 near the Caramanico's centre (left side of photo)

View is to ENE; in the foreground the Orta river is eroding toes of gully-channeled earth

APPLICATION AND VALIDATION OF MODEL WITH RESPECT TO CARAMANICO

EO data and land-use classification

Wide-area, EO surface change data from Landsat images (TM5 and ETM + 7) covering the test site were available from 1987 to 2000 and SAR PS results from 1995 to 2000. These are the 2 temporal EO surface change datasets which have been integrated within a GIS (ARCVIEW).

Landsat image processing was carried out at CNR ISSIA, Bari using ENVI v. 4.0. A detailed discussion of the methodology and further results are given in Blonda *et al.* (1996) and Tarantino *et al.* (2004). However, using data from the test site area, it was only possible to recognise 4 or 5 land-use classes with a sufficient degree of confidence to be used within the geotechnical model, i.e.:

— arboreous (woodland);
— bare soil/rock;
— agricultural (cultivated land);
— artificial (man-made structures);
— natural rangeland (a subdivision created mainly from cultivated land).

From these few broad classes and limited resolution (30 m) it was not possible to obtain ideal levels of geotechnical impact. For example, the exact nature of surface changes and their relationship with individual slopes (in terms of temporal positive or negative FS impacts) could not be established. Nevertheless, despite this shortcoming some promising generalised results were obtained.

SAR PS analysis was carried out at the Department of Physics, Bari University. A detailed description of the technique and further results are given in Bovenga *et al.* (2004). Reliable values were only obtainable from the urban areas and as a result of this limitation there was a considerable difference in the areas covered by the 2 EO techniques for the test site.

Development of the model and geotechnical impact maps in a GIS

The sequence of the first 7 maps (Figs. 5–11) shows selected examples obtained through the manipulation and interrogation of the ground based data in a GIS (ARCVIEW). The initial input layers for the model consist of the principal geological units (G). At Caramanico they are:

1. Geology (G)
   G1 — artificial ground
   G2 — water laid and alluvial sediments
   G3 — debris flow/slope colluvial deposits
   G4 — carbonate megabreccia
   G5 — marly mudstones
   G6 — highly tectonised limestones.
   This input data is used to obtain geotechnical classes
2. Slope map (S) — with values 0–90°.
3. Landslide map (L) — this is required to distinguish areas with potential for either first-time failure or reactivation (Fig. 5):
   0 = no landslide
   1 = quiescent landslide
   2 = historical or active landslides
4. Land use classification map (C_i) — for the i-th year.

Fig. 5. Historical or active landslide deposits (red) and quiescent or inactive (brown)

Extension: 10,450 m (W–E), 8,900 m (N–S)

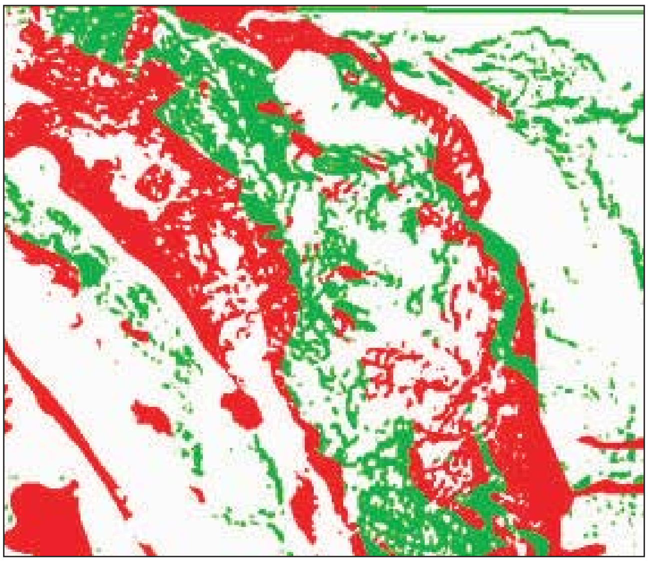

Fig. 7. Slopes below the slope threshold (white), slopes in non-brittle soils or soft rock above the threshold (green) and brittle soil and soft rock (red)

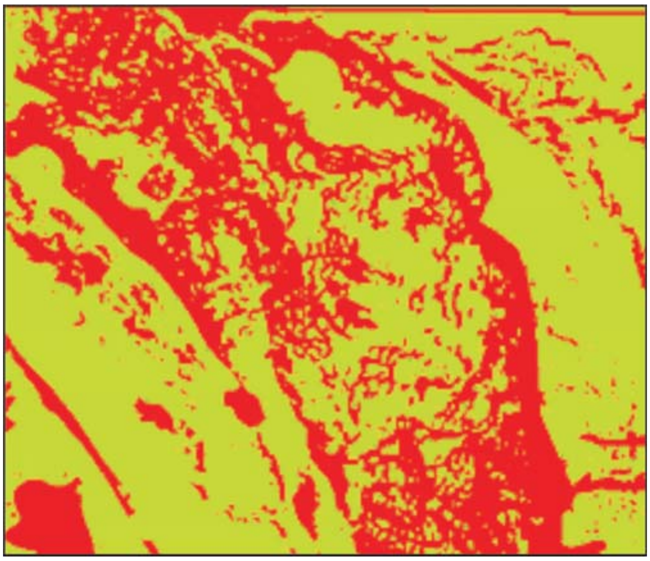

Fig. 6. Slope angles for all lithologies which are below the threshold allocated to the lithology (green-yellow)

Slopes above the threshold are in red

Fig. 8. Distribution of engineering rocks (grey) and soils (brown)

Fig. 9. Non-brittle soil or hard rock (green) or brittle soil (red)

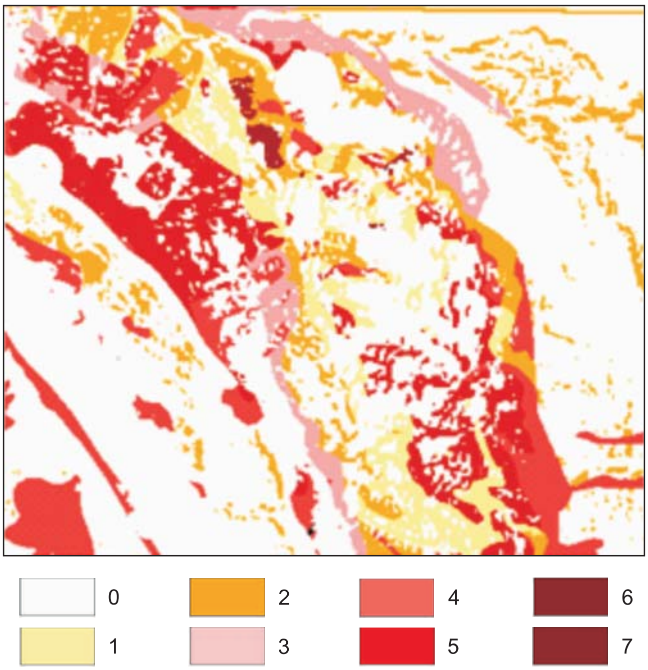

Fig. 11. The distribution of all 7 susceptibility levels

Fig. 10. Intersection of landslipped areas with a map showing slope thresholds and material brittleness

Pink — active or historical landslides; brown — quiescent landslides above slope threshold in brittle soil or soft rock; red — quiescent slides in non-brittle soil or hard rock

Algorithm to calculate potential slope impact from land-use change

In order to use the conceptual model to produce an assessment of slope impact, i.e. potential slope deformation from a land-use change at a FS = 1, it is necessary to introduce (a) slope thresholds, (b) a geo-mechanical division between soils and rocks and (c) an indication of material brittleness, i.e.:

1. A slope threshold map (T)

This is obtained from the geology map by assigning each lithology, i.e. G1–G6, for the Caramanico test site, a slope threshold value, S1 to S6. A single threshold figure for each geotechnical class is the simplest level to use and is comparable to an "ultimate angle of stability", i.e. an angle, below which natural slopes for that geotechnical class are considered to be stable. This approach is conservative, but has the advantage of providing a quick overview of slopes in a study area. More refined analysis would include provision for variations in groundwater conditions and in areas of potential first-time slides slope angle-height relationships.

S1 = 10°
S2 = 10°
S3 = 20°
S4 = 45°
S5 = 6°
S6 = 40°

2. Map of threshold areas (ST) (Figs. 6, 7)

1 if S>T
0 if S<T

3. Engineering soil-rock map (Fig. 8)

Obtained through G, 1 if soil, 0 if rock
1 if G = 1, 2, 3, 5
0 if G = 4, 6

4. Brittleness map (B) (Figs. 9, 10).

Obtained through G, 1 if brittle soil or soft rock, 0 if non-brittle soil or hard rock. In the Caramanico area the marly mudstones (G5) although a soft rock, may have the mechanical characteristics of an engineering soil (in a worst case scenario)

1 if G = 1, 3, 5
0 if G = 2, 4, 6

5. Map showing susceptibility to deformation at failure or reactivation (SC)
   0: ST = 0
   1: ST = 1, L = 1, B = 0
   2: ST = 1, L = 0, B = 0
   3: ST = 1, L = 0, B = 1, SR = 0
   4: ST = 1, L = 0, B = 1, SR = 1
   5: ST = 1, L = 1, B = 1
   6: ST = 1, L = 2, B = 0
   7: ST = 1, L = 2, B = 1
6. Final warning of increased susceptibility to slope instability

Deformation warning level = Susceptibility level (SC)* presence of negative change in the time period being considered.

For the Caramanico area SC levels 6 and 7 contain historic or active landslides and with slopes above the threshold are considered to be most susceptible to deformation following ground surface change. SC levels 2 to 4 are areas of potential first-time slides where FS and susceptibility is more uncertain. SC level 1 includes failed non-brittle materials (i.e. soils of low plasticity) and ancient inactive landslides-/colluvium with limited potential for reactivation. Figure 11 shows the distribution of all susceptibility levels (SC) for the Caramanico area.

EO landsat data and temporal surface change for warning levels

Figure 12 shows all surface changes that may have had a negative impact on stability in terms of the 1–7 warning levels of Figure 11. However, there were difficulties with mis-classification (see below) and whilst it was possible to recognise 4–5 land-use classes using historic Landsat images, each with a potential geotechnical impact, it was found that the changes from any land-use class to "artificial structures" were the most consistent and more easily verified. However, even with this single change transition from the vegetation classes, there were also some minor mis-classifications with "bare soils/rock". Despite the limitation, this class transition was chosen to both illustrate and validate the methodology. Fortuitously, it could also be argued that it resulted in point and line loads or unloads, rather than areas of vegetation changes and therefore had the most positive/-negative effects on slope instability. Nevertheless, this problem with reliability reduced the usefulness of the EO data, for example it was not possible to add to the temporal trends of the vegetation changes found in the aerial photograph study.

Figure 13 summarises all the ground surface change transitions to "artificial structures" obtained through Landsat image processing for the dates 1987 to 2000 superimposed on a 1997 orthophoto. Four land-use class transitions were used to obtain the areas with this negative change. These are the areas that are subject to warning, with the different levels of warning, 1–7 corresponding to the levels of susceptibility to deformation. A negative change does not create a warning in the case of level 0.

It has been assumed that the worst condition applies, i.e. those negative effects are dominant following the change from vegetation classes to artificial structures. Figure 14 is a zoomed image of the Caramanico urban area showing the transitions to artificial structures from 1987–2000 in relation to the levels of warning, 1–7. The 4 class transitions are based on a greatest probability criterion, i.e. at least 25%.

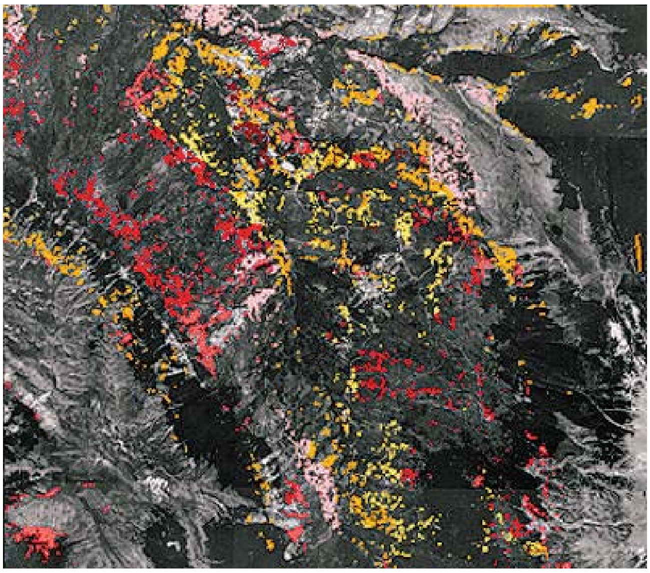

Fig. 12. All ground surface changes with negative geotechnical impact with respect to slope instability (1987–2000)

This includes the surface changes to artificial structures and the removal of trees to form either cultivated land or bare soils (see Figure 11 for susceptibility levels colour scale); extension: 10,000 m (W–E), 8,900 m (N–S)

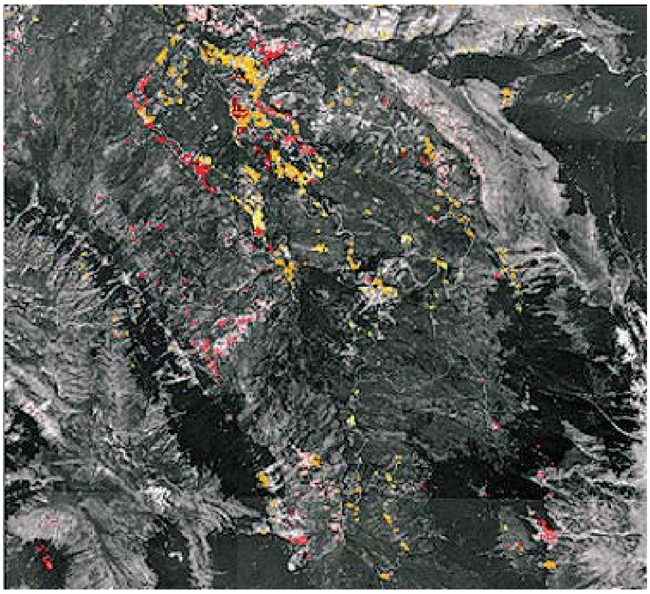

Fig. 13. All ground surface transitions to artificial structures/bare soils (1987–2000) overlain on an orthophoto of 1997

See Figure 11 for susceptibility levels colour scale

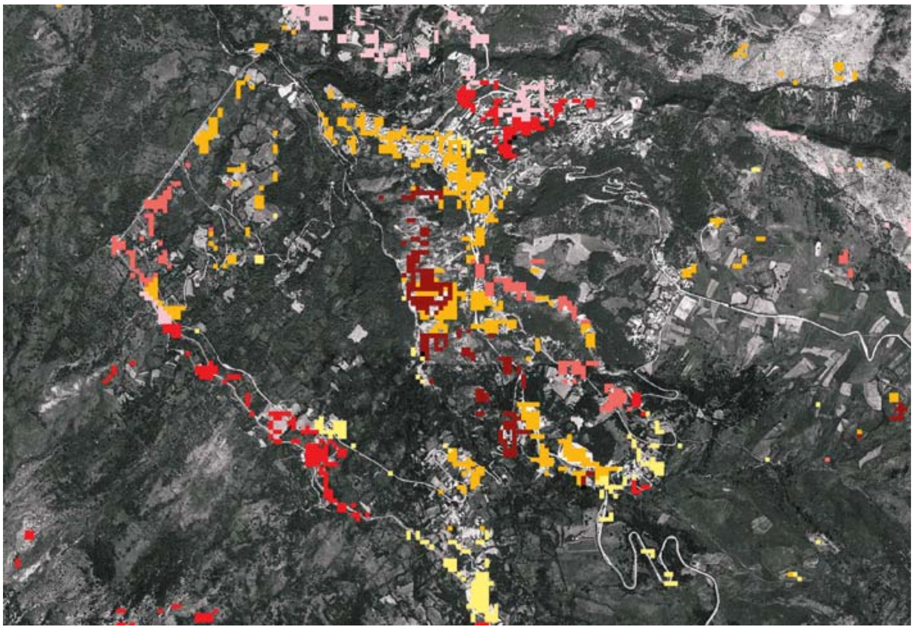

Fig. 14. Zoomed image of Caramanico showing change (25% probability threshold) to artificial structures with coloured levels of warning

1— light yellow, 2 — dark yellow/orange, 3 — pink, 4 — light red, 5 — dark red, 6 — dark brown, 7 — is not present; extension: 4,550 m (W–E), 3,050 m (N–S)

Interpretative difficulties with temporal classification of Landsat EO Data

In addition to the interpretative problems of mis-classification from a single change, there were also yearly oscillations from 1994 to 2000, between classes of arboreous (trees) to cultivated land and arboreous to bare soil, despite using a 70% probability of correct land use class. Some of the oscillations may have been real, but with a 70% threshold, it seemed unlikely within this period that they were on an annual basis. To overcome this problem the change outputs were firstly restricted to those pixels critical for instability, which were expected to be "one way". For example, the surface changes which occurred from any land-use class to artificial structures. A comparison could then be made with the outputs obtained previously. Secondly, CNR ISSIA introduced an extra vegetation class of "rangeland", in an attempt to suppress the oscillation effect. This class consisted of deeper rooted plants than cultivated areas, but it was considered that it was generally of less benefit to stability (through root reinforcement and evapo-transpiration) than trees.

With the assumption of a 4 class initial condition on the processed Landsat images, the temporal results suggested that from 1987–2000, 20% of the test area had been subjected to surface change (with a 70% threshold). With a 5 class initial condition this increased to 28%, reflecting the greater number of inter-vegetation class transitions and apparent uncertainty. However, when aggregating the vegetation classes from the 5 classes and only considering the change to artificial and bare soil the number of changes reduced to around 5–6% compared to 11% with 4. This suggested the 5 classes were more stable for this temporal surface change transition. It is of interest to note that, for the pixel change from aggregated vegetation classes to artificial structures in the 7 warning classes there was a 0.35% change in the 13 year period, while from vegetation to bare soil the figure was 0.4%.

For each year of analysis there may have been different areas of cloud or snow masks. In addition, when applying a probability threshold to an image, a part not masked may not have been classified because no class had reached the threshold for that year. The gaps left were filled by starting with the first classification in 1987, assuming in the second and subsequent classifications that the missed pixels assumed the land-use class of the previous year.

"One way" pixel change to artificial/bare soil/rock, plus PS, GPS and springs

Figure 15 combines both cumulative (1987–2000) one-way pixel changes to artificial and bare soi/rock also using aggregated vegetation classes with a 70% probability threshold. Compared to Figure 14 there is a reduction in the number of change pixels and this possibly represents the most accurate assessment of "negative" slope impact from the 4 initial land-use classes for the Caramanico area. In addition, the moving PS points have been added and are shown by light blue crosses. The light blue circles show positions of GPS stations from the Caramanico network which have been geo-referenced in the GIS and show average downslope movements of between 15 to 44 mm year from 2002 and 2005 (Wasowski *et al.*, 2005). The dark blue, dot-line symbols are groundwater springs and represent the centres of the "areas of potentially high water pressures". They (the springs) have been included to show associations with the deformation and ground surface change areas. For the latter, the dark and bright red areas represent the highest levels of warning. The figure thus illustrates "negative" anthropogenic slope impact in and around the town and the value of integrating the deformation measurements made on the ground with the EO surface change results. There are also some surface change impacts in rural areas, but these lack deformation measurements and may be of less significance in terms of risk.

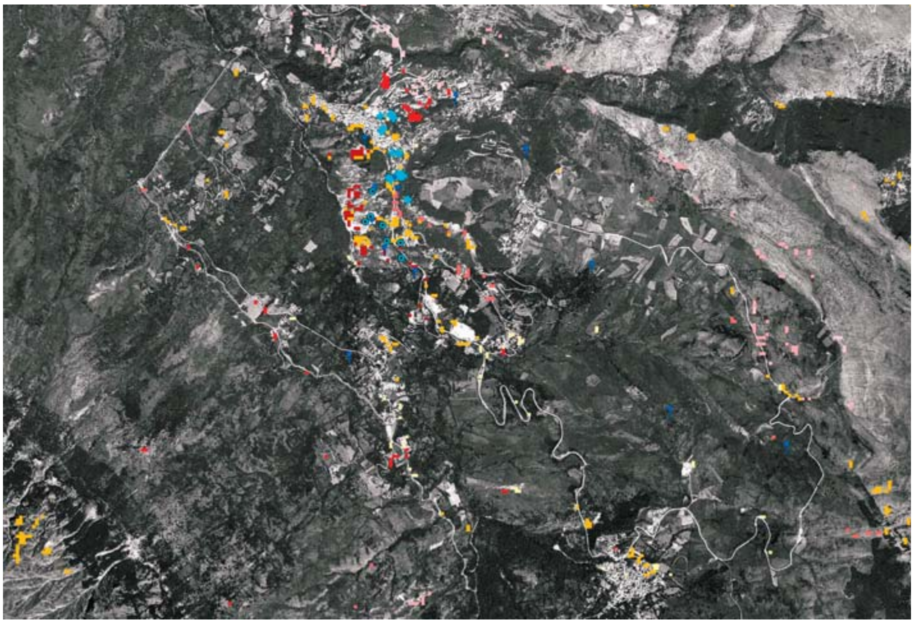

Fig. 15. Combines all surface changes to artificial structures and bare soil (1987–2000) from the aggregated vegetation classes assuming a one-way change with a 70% probability threshold

The colours represent levels of warning with dark brown at level 6; see Figure 11 for susceptibility levels colour scale; the light blue crosses — moving PS points; the light blue circles — GPS points showing deformation, dark blue dot-line symbols — groundwater springs; extension: 7,000 m (W–E), 4,800 m (N–S)

In summary, there seem to be some connections between the deformations and concentrations of historic (13 year) ground surface change within the urban area. For this demonstration the data have all been presented cumulatively, but it is also possible to use the GIS to illustrate annual change, i.e. to highlight years where change has accelerated and vice-versa. Practically, such maps or map series show decision-makers where future surface changes may continue to aggravate the deformation areas recorded by the PS and GPS.

"One way" pixel change with provision for prior multiple change

The previous examples of one way change (e.g. Fig. 15) have selected pixels on the basis of a single class transition within the 13-year period to either artificial ground or bare soil. A more flexible procedure also included a single one way pixel change, but also allowed the provision for multiple change from vegetation to bare soil prior to the "artificial change" event and the possibilities of artificial to bare soil/rock change after the "one-way" change. The former is realistic in the time scale considered and the latter can be included because of the current uncertainty in the temporal classification of the vegetation to artificial/bare soil/rock transition. A further condition of this approach was that the artificial class should also be present or remain until the last year of processing. For the transition to bare soils a single one way pixel assumption was assumed. Figure 16 shows the surface change outcome for pixels classified as both artificial and bare soil/rock in relation to the warning levels. It illustrates that with this pixel recovery, the percentage of change for the artificial case increases by more than 50%, but still covers a comparatively small, but perhaps still acceptable part of the image.

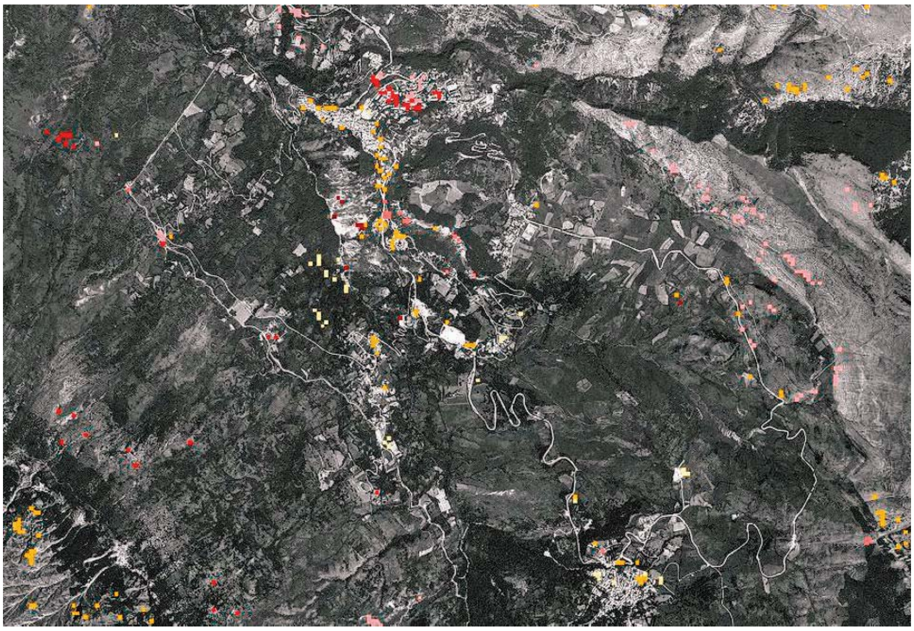

Fig. 16. One way pixel change to artificial and bare soil from aggregated vegetation classes with 70% probability threshold which has included the possibility of multiple changes to bare soil prior to the one way "artificial event" and the possibility of "artificial" to bare soil after the event

See Figure 11 for susceptibility levels colour scale

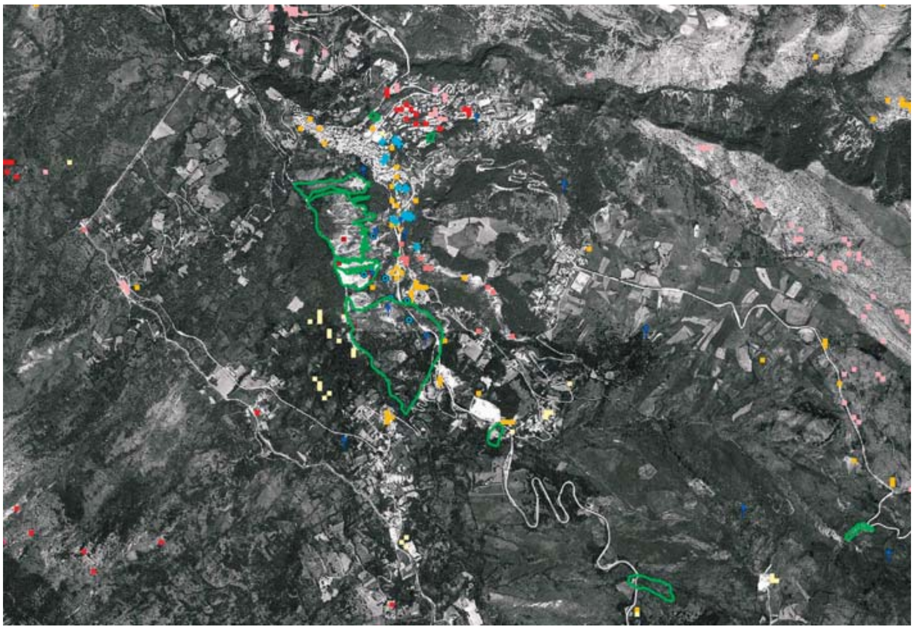

Fig. 17. Combines historical/active landslide distribution between 1989–2000 (green outline), springs (dark blue) moving PS (cyan crosses), moving GPS (cyan circles) and levels of warning from surface one-way pixel change to artificial structures and bare soil

See Figure 11 for susceptibility levels colour scale); extension: 5,650 m (W–E), 3,900 m (N–S)

Validation with respect to landslide inventory, GPS and PS data

The warning map results can be integrated with other EO and ground data. Figures 17 and 18 combine the distribution of historical/active landslides in the period 1989–2000 (green outline), the distribution of main groundwater discharge areas (springs shown in dark blue), as well as data relevant to ground surface deformations detected and monitored via PS InSAR and GPS techniques. (only moving PS with an average velocity >2 mm/yr are included as cyan coloured crosses). Similarly, GPS points with significant displacements, i.e. an with average velocity ≥1 cm/yr are shown as cyan circles with dark centres. The superposition of these different data indicates there may be connections between the temporal build up of the ground surface changes (to artificial structures) around the urban areas with active landslide areas and the deformations obtained from the PS and GPS monitoring. It is of interest that, in the majority of cases, the areas (pixels) showing different levels of warning do not appear to overlap the stable areas marked by a non-moving PS, shown as purple crosses in Figure 18. The warning maps also draw attention to surface change impacts to the town areas situated in the vicinity of groundwater discharge (springs) For example there is a close association between the location of active landslides, springs and moving PS and GPS points in the southern periphery of the town.

There is a general correspondence between the surface change areas (vegetation to artificial structures and bare soils/rock) shown in Figures 9 to 12. However, as a result of using different image processing procedures there are considerable differences in detail. The question arises as to which one

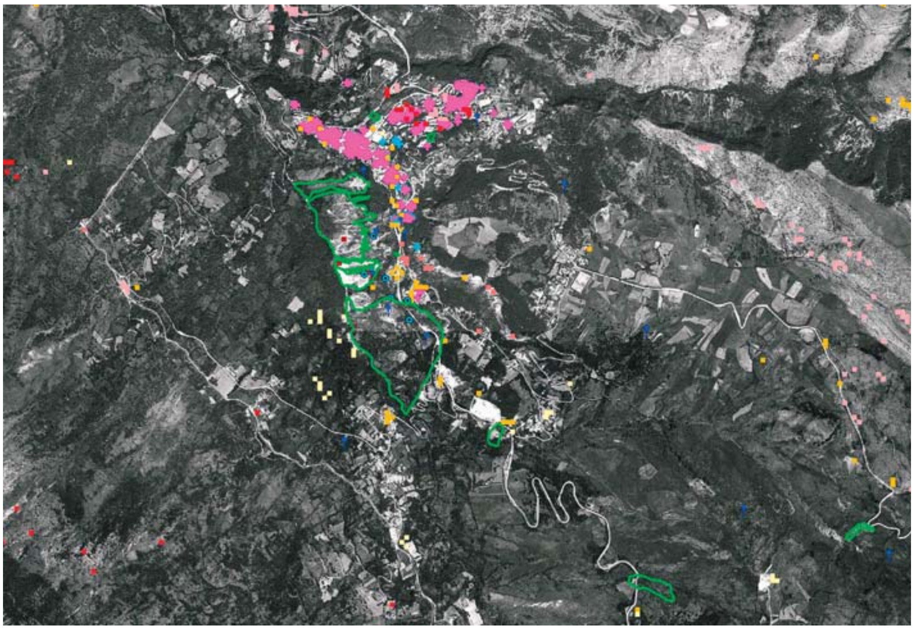

Fig. 18. As Figure 17, except non-moving PS points (purple crosses) are included

The levels of warning do not appear to overlap the non moving points; see Figure 11 for susceptibility levels colour scale should be used to give the greatest reliability of anthropogenic impact, at the same time ensuring that nothing critical is missed? At present, it would seem that there are no obvious answers. Additional ground truth would clearly be of value, but applications in areas where this is not always possible may require a procedure that, at its simplest level uses a max and min criteria. An end-user would then have to decide, possibly with the help of local knowledge, PS and other ground based data whether the warnings were significant or not.

SUMMARY AND CONCLUSIONS

This paper has put forward a new approach to the production of slope instability "warning maps" using integrated EO techniques for obtaining temporal ground surface change and ground based data. The geotechnical inference model firstly uses GIS topographic and geological ground data to identify potential levels of deformation in slopes which are close to a factor of safety of 1.0, i.e. they are susceptible to mass movement. Secondly it integrates EO surface change data in ARCVIEW to show levels of warning with respect to that deformation. It uses a simple geotechnical framework within which data inputs and outputs can be selected and managed.

The model has been developed using data from the Caramanico area in Italy, but its structure is flexible and can be adjusted for use in other landslide-prone areas. The basic premises of the model are:

— definition of susceptibility levels;
— warning resulting from negative land-use change detected through EO;
— levels of warning dependent on levels of susceptibility to deformation.

Validation of the model in the Caramanico test area using Landsat data from 1987 to 2000 has shown that changes from vegetation to artificial structures/bare soil assuming 5 initial classes were perhaps most reliably reproduced, i.e. with less mis-classification, although the 2 classes were frequently confused. There were also problems with temporal oscillatory changes, especially between the vegetation classes that not yet been completely resolved for the use of these transitions in practical situations.

For Caramanico, 7 levels of warning were defined, based on lithology and potential deformation. Fortuitously, it could be argued that the dual change (to artificial and bare soil/rock) from the vegetation classes may have had most negative impact with respect to slope instability and this change has been used to validate the model.

The results suggested that there were some spatial relationships between the temporal build up of ground surface changes (artificial structures) around the urban areas over a 13-year period (1987–2000) with active landslide areas and deformations obtained from PS and GPS measurements. The warning maps also drew attention to surface change impacts to areas of the town in the vicinity of groundwater discharge (springs) where future instability should be considered.

A difficulty that remains with the Landsat data however, is in a choice of an image processing procedure to produce the maps showing areas of change. For example, there are large differences between surface change data which have been derived with a greatest probability assumption (25% for the Caramanico classes) and those with a 70% threshold. Within the validation exercise it has also been shown that the number of pixels showing overall change and warning are reduced by restricting the oscillations of the temporal land-use class transitions, i.e. for artificial structures, to a one way change which is more likely in a 13 year period. Similarly, when the initial classes were increased from 4 to 5, the resulting aggregated changes from the 3 vegetation classes to artificial structures/bare soils/rock decreased even further.

Until the problems attached to the temporal transitions within the vegetation classes are resolved these impacts can not really be assessed with confidence in relation to positive or negative impacts on slope instability within the rural areas. As demonstrated here, the first results from the methodology suggested that the cumulative aggregated changes from vegetation to artificial structures/bare soils/rock using 5 initial classes, may show most future promise as an EO indicator (warning) of negative anthropogenic interference on slopes.

Practically the Landsat images give a general overview of the vegetation to artificial ground/bare soil/rock temporal transition in the Caramanico test site area, but reliability is lost at detailed slope scales. The usefulness of such images in real decision making is clearly very much improved when combined with PS and related ground data.

Notwithstanding these problems, it seems that a workable prototype of an integrated model which links EO land-use change, deformation, and ground based data in a GIS which provides warning of possible future slope instability has been achieved. The methodology and datasets also provide a general regional overview of historic man-made geotechnical impact and might be useful in a number of other applications. This approach, as it stands, thus adds value to the data inputs and provides information that might assist in many aspects of planning and engineering decision support.

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