LANDSLIDE HAZARDS

CEOS DISASTER MANAGEMENT SUPPORT GROUP

PURPOSE

This report is a summary of current and potential uses of EO data applied to the assessment of landslides. Our main objective is to assess the role of EO data by improving our understanding of the causes of ground failure and suggesting mitigation strategies. This brief working paper represents the combined efforts of the landslide team listed below. This report is listed at (http://disaster.ceos.org/landslide.htm) to invite additional comments from the disaster management communities. Relevant background information is included to inform a very diverse disaster management community.

Summary Landslide Recommendations to the Space Agencies:

1. The future availability of space borne InSAR data for slope motion monitoring is not yet clear. The European ERS SAR is a useful system for repeat-pass SAR interferometry because of the high stability of the sensor, good orbit maintenance and the fixed operation mode. Other orbital SAR systems needed to provide similar orbit parameters of less than +/- 1km. The European follow-on sensor ASAR on board the ENVISAT, as well as other planned SARs, provide many different operation modes, which will reduce the availability of repeat pass interferometric data. On the other hand, the higher spatial resolution of some of these sensors would be of interest for mapping also small slides. The important contributions of InSAR to landslide hazard management and to a range of other environmental monitoring tasks would justify a long-term SAR mission optimized for InSAR applications.

2. There is a requirement for Space agencies to provide archival background SAR images for all future SAR systems to perform repeat pass InSAR analysis to monitor very slow movements of slopes and other areas.

3. A guideline for landslide hazard emergency response scenario is presented at the end of the Landslide report (section 7). This will facilitate the space agencies to acquire appropriate data to meet the timely delivery of image maps to relief agencies. An internet image distribution system will facilitate emergency response in affected areas

Landslide Team Accomplishments: (2000-2001)

1. The Landslide Hazard team concentrate its efforts on 3 test areas: Fraser Valley Landslides, Canadian Cordillera; The Corniglio Landslide, Northern Apennines, Italy;Itaya Landslide, Japan. The choice of the sites is based on (1) geological diversity;(2) the types of landslides, (3) current threat to populated areas and infrastructure, and (4) existing work conducted by the current Landslide team.

2. Earthquakes, excessive rainfall, and volcanic events are the triggers of the landslides, and this allows the CEOS landslide team to work closely with the other working groups on earthquake, volcanic and flood hazards. Because of this, the Landslide team is participating actively in the development of the IGOS Partners Geohazards Theme.

3. The Landslide Hazard team is producing a special issue Journal issue in "Engineering Geology": for May 2002. This special issue is the result of a special session on "EO application to Landslides" at the European Geophysical Congress in Nice, May 2001.

Background

The term landslide denotes "the movement of a mass of rock, debris or earth down the slope". In addition to this definition it can be stated that the movement occurs when the shear stress exceeds the shear strength of the material. The analysis of a possible increase of the shear stress and/or decrease of the shear strength of the material is integral to fully understanding landslide mechanics and applying the most appropriate remedial measures.

The factors contributing to an increase of the shear stress include:

- removal of lateral and underlying support (erosion, previous slides, road cuts and quarries)
- increase of load (weight of rain/snow/ash, fills, vegetation)
- increase of lateral pressures (hydraulic pressures, roots, crystallization, swelling of clay)
- transitory stresses (earthquakes, vibrations of trucks, machinery, blasting)
- regional tilting (geological movements)

Factors related to the decrease of the material strength include:

- decrease of material strength (weathering, change in state of consistency)
- changes in intergranular forces (pore water pressure, solution, fracture and crack propogation)
- changes in structure (decrease strength in failure plane, fracturing due to unloading)

Globally, landslides cause approximately 1000 deaths per year, causing property damage of approximately US $4 billion (Alexander,1995). Landslides pose serious threats to settlements, and structures that support transportation, natural resources management and tourism. They cause considerable damage to highways, railways, waterways and pipelines. They commonly occur with other major natural disasters such as earthquakes (Keefer, 1984), volcanic activity (Kimura and Yamaguchi 2000), and floods caused by heavy rainfall. Each type of earthquake-induced landslide occurs in various geological environments, ranging from steep rock slopes to gentle slopes with unconsolidated sediments. The area affected by landslide in an earthquake correlates with the magnitude, geological conditions, earthquake focal depth, and specific ground motion characteristics (Keefer 1984, 1994). Damage from landslides and other ground failures have sometimes exceeded damage directly related to earthquakes. In many cases, expanded development and human activities, such as modified slopes and deforestation, can increase the incidence of landslide disasters. Recent development in large metropolitan areas intrudes upon unstable terrain. This has thrown many urban communities into disarray, providing grim examples of the extreme disruption caused by ground failures.

Landslides can be rapid or slow, and occur in a wide variety of geologic environments, including underwater. The secondary effects of landslides can also be very destructive. Waves generated by landslides entering rivers, lakes or other bodies of water have caused substantial damage.[2] Other

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[2] Lituya Bay, Alaska, July 10, 1958 a Magnitude 8 earthquake triggered a landslide that caused a water splash wave that reached 1,720 feet up the mountain slope (ref: See Steinbrugge, K.V. in References at the end of this Team report); and Vaoint Reservoir, Italy, October 9, 1963 a massive landslide caused a tremendous water wave that swept 300 feet above and over both dam abutments, causing a major flood that killed an estimated 2,600 people (ref: See Kierch, G. A. in References at the end of this Team report).

secondary effects include upstream and downstream flooding due to landslide dams and dam breaks. (Evans and Savigny, 1994).

Types of Landslides

In general, there are many landslide classifications, but no single classification has universal application. Six distinct types of landslide movements are briefly described:

- A *fall* or rockfall comprises a detachment of soil or rock from a steep slope and the more or less free and extremely rapid descent of the material. Rockfalls usually occur where a steep rock face is well-jointed. The rockmass disintegrates into numerous blocks that fall, bounce, and roll after detachment. Rockfalls are a constant problem along transportation routes through rocky terrain.
- A *topple* is a forward rotation out of the slope of a mass of soil or rock about a point below the centre of gravity of the displaced mass.
- A *landslide*, in the restricted sense of the word, is a generally rapid to very rapid downslope movement of soil or rock bounded by a more or less discrete failure surface, which defines the sliding mass. An essential element of sliding is that the movement takes place as a unit portion of land, which implies that there are no movements within the slipped block (the internal movements). Sliding in rock and soil may occur along a curved, curvilinear, or a multi-planar surface and is usually retrogressive. Landslides are usually slow moving, but can damage or destroy structures founded on the moving mass. The term rockslide is used when a rock mass slides on a detachment surface. The term landslide most used by non–specialists usually refers to slow moving materials that can damage or destroy structures founded on the moving mass
- *Sagging* is defined as large-scale deep seated deformations that are under the influence of gravity and occur in competent rocks and in zones where erosion has created deep valleys and therefore an unstable situation.
- *Spread* is defined here as an extension of a cohesive soil or rock mass combined with a general subsidence of the broken mass of cohesive material into softer underlying materials
- A variety of *flows* exist and they grade into all other types of slope movements. For example, debris flows can be generated from debris slides or by extreme forms of stream flow erosion. Debris flows are smaller and less rapid than rockfalls but can be very destructive. They occur when a saturated mass of surficial deposits moves down a stream channel, and are characterized by significant relief and sharp, well-defined flow boundaries. Heavy rains often trigger initial failure. They can also occur following the bursting of a natural dam formed by landslide debris, glacial moraines, or glacier ice.

EO data uses for landslides

The use of EO data is discussed as follows: mapping landslide related factors; characterization of landslide deposits monitoring; preparedness (monitoring and mitigation); response; research challenges and CEOS demonstration sites. This report also includes the uses of synthetic aperture radar (SAR) and interferometric SAR (InSAR), high spatial-resolution multispectral (IKONOS), and multispectral (Landsat, SPOT, IRS) data for landslide studies. Future satellites, such as the European follow-on sensor ASAR on board of ENVISAT, the Canadian RADARSAT-2 and the Japanese ALOS are also discussed.

Mapping landslide related factors

The main contribution of EO data is to provide the morphological, land use, and geological detail to assist in determining how the landslide failed and what caused the failure. Where failure could occur can be addressed in a more regional geographic information system (GIS) analysis as a necessary first step in risk analysis. This is because the factors contributing to slope failure at a specific site are generally complex and difficult to assess with confidence.

GIS techniques are used increasingly for regional analysis and prediction. Several digital data sets are typically used for such analysis. These can include an inventory of landslides; seismic records; large-scale geological mapping; extensive geotechnical data on rock properties; high-resolution digital elevation data, and suitable high-resolution remote sensing data and aerial photographs. This mapping procedure can be used to produce hazard risk maps that will assist in emergency preparedness planning and in making rational decisions regarding development and construction in areas susceptible to slope failure. Landslide risk studies are still not very common. This is mainly due to the fact that it is very difficult to represent landslide hazard in quantitative terms related to probability over large areas. This is because landslides do not have a clear magnitude/frequency relation, as is the case for floods or earthquakes. Lithologic and vegetation/landuse mapping use Landsat TM and SPOT and IRS and IKONOS images.

Detailed slope information is essential for reliable landslide inventory maps. Currently, topographic maps and digital elevation data are used. Slope affects surface drainage and is an important factor in the stability of the land surface. Current research has shown that airborne and satellite InSAR techniques are being used to produce detailed slope information (Singhroy et al 1998, Singhroy and Mattar 2000, Kimura and Yamaguchi 2000) This allows a more accurate interpretation of slope morphology and regional fracture systems with topographic expressions. However, further research is needed in updating local slope information from suitable InSAR pairs using ERS1& 2 tandem, JERS-1 and RADARSAT-1. The large archive of SRTM data will assist in providing regional slope maps.

Characterization of landslide deposits

Two distinct approaches can be used to determine the characteristics of different landslides from remotely sensed data. The first approach is to determine the number, distribution, type, character, and superposition relations of landslides using available remotely sensed data. The second approach complements the first one by measuring dimensions (length, width, thicknesses and local slope) along and across the landslides using imagery and topographic profiles (e.g. laser altimeter profiles). Where possible these dimensional data should be compared to any previous studies. With these approaches, it is possible to derive qualitative and quantitative parameters on landslides that are necessary for improved understanding of landslide processes.

Distribution and superposition (Approach 1)

There remain significant limitations on the uses of remotely sensed EO data for landslide studies. The majority of landslide research carried out by remote sensing to date falls into the category of inventory mapping. The principle problem is that remote sensing data rarely had a high spatial resolution to be useful in the study of anything but the largest landslides. However, both space-and-airborne remote sensing systems now have resolutions that permit detailed geomorphologic mapping to be conducted. With the advent of repeat-pass interferometry (*see* section 3.2.2) it has become possible to detect subtle changes (at mm scales) in the landscape such as seismic displacement (e.g. *Massonnett et al.,* 1993). However, landslides are difficult to study using radar interferometry (e.g. *Fruneau et al.,* 1996) because they can experience ground deformations in excess of the phase gradient limit (*Carnec et al.,* 1996) and which eliminate interferometric correlation (*Massonnet and Feigl,* 1998). Attempts are being made to better integrate radar interferograms, field measurements, and ancillary remote sensing of landslides to obtain “calibrated” interferograms which will provide useful geologic and geophysical information to the landslide monitoring community (e.g. *Bulmer et al.,* 2001). However, even such improved technologies are, however, rarely utilized to their full potential in hazard assessment.

Data from both the visible (*Brunsden et al.,* 1975; *Doornkamp et al.,* 1979) and microwave (e.g. *Singhroy et al.,* 1998; *Bulmer and Wilson,* 1999) portions of the electromagnetic spectrum can be used to map the geomorphology of landslides. The application of photogeologic mapping techniques (*Varnes,* 1974) provide a framework for developing mapping strategies will assist in the interpretation of these differing data. Geological units can be defined on the basis of morphological, textural, and structural characteristics visible in the images and related to the existing geologic maps.

Where possible, the highest resolution data that is available should be obtained and used to identify a range of geomorphic features and dimensional data on landslides of interest. Tables 1 and 2 provide guidelines for discerning these features in EO data.

Location	L m	W m	T m	A km^2	θ	V km^3	H m	H/L
Headscarp								
Upper track								
Middle track								
Lower track								
Depositional zone								

***Table 1**. Dimensional data to be obtained on landslides using remotely senses data L = length, W = width (min, max), T = thickness, θ = slope, V = volume, H = height from the top of the adjacent scarp to the base of the slope of the landslide, H/L = average friction coefficient given by the tangent of the line connecting the top of the scarp and the toe of the deposit (see Cruden, 1980; Shaller, 1991). In the absence of any high-resolution topographic information a first order volume can be estimated using the aerial extent and an estimated thickness.*

Features	L m	W m	T m	A km^2	θ	V km^3	H m	H/L
Tension cracks								
Ridges								
Levees								
Overtopping								
Superelevation								
Material sizes								
Material type								

***Table 2.** Additional geomorphic parameters to be obtained on landslides using remotely sensed data. Note that determinations of velocity based on climbed and/or overtopped obstacles only give an estimate for one short segment. It assumes conservation of energy for the material that climbed the obstacle, with the energy required to overcome gravity originating in the kinetic energy of the landslide (Shreve, 1966). Estimates of mean velocity can be made by calculating the tilt of the flow surface and the radius of curvature of the flow bend in a channel (Johnson, 1984).*

When selecting and using remotely sensed data the goal should be to determine: 1) the local lithology, 2) aerial extent of landslide deposits at each site, 3) local age relationships, 4) examine evidence for the cause and frequency of emplacement, 5) look for differences in landslide morphologies as keys to the magnitude and types of mass movement events, and 6) measure dimensions, slopes (local and regional), volumes, and material sizes.

Surface topography studies (Approach 2)

Landslide surface structures and roughness provide information on flow emplacement parameters (such as emplacement rate, velocity, and rheology). Using parallax equations measurements of the heights of surface structures can be made from stereo aerial photographs (*Lillesand and Kiefer,* 1987) and radar images (*Plaut,* 1993). Features such as the peak and the trough of folds on landslides can be measured and fold amplitude calculated. In addition, data from newly developing laser altimeter instruments can be used to measure features of landslides such as ridge wavelengths and amplitudes, thickness variations in debris aprons as well as local, regional and underlying slope. Laser altimeters tend to have vertical and radial accuracy of <1 m (e.g. *Krabill et al.,* 2000). The spacing between pulses along each orbital track or flight line varies depending on the instrument, but is typically $\leq$ 5 m. Across-track spacing depends on the number of available orbits or flight lines. Thus, the inter-track spacing will decrease as more data is obtained. Using laser altimeters it is also possible to calculate surface roughness in two ways: large-scale slopes directly from the topography (*Aharonson* et al., 2001), and sub-footprint scale slopes from data on the returned laser pulse width (*Garvin and Frawley*, 2000; *Smith et al.,* 2001). Roughness is defined as the topographic expression of surfaces at horizontal scales of centimeters to a few hundred meters. Individual topographic profiles from laser altimeters can be used to construct plots of the Allan variance or structure function, versus horizontal step size. A self-affine, or fractal surface, is characterized by a power-law scaling between these parameters (*Shepard et al.,* 1995). For a two-dimensional profile, the Hurst H exponent is related to the fractal dimension D as $D=2-H$. Surfaces with low values of H roughen more slowly with increasing horizontal scale, while surfaces with high H have vertical roughness that increases rapidly with step size. For different landslides the Hurst exponent and the value of the Allan deviation at unit length (equivalent to the RMS slope at unit scale), can be compared with those measured for other geologic surfaces (e.g. *Campbell and Shepard,* 1996; *Bulmer et al.,* 2001). This examination of the statistical roughness of geologic surfaces can be used to greatly improve in the interpretation of remotely sensed data at all wavelengths.

Surface roughness affects the behavior of scattered microwaves. Because the roughness of landslides has not been studied in detail, a quantitative comparison with other geologic surfaces such as lava textures has not been possible. Studies of roughness have mainly focused on basaltic pahoehoe and a'a lava surfaces (e.g. *Campbell and Shepard,* 1996). Only recently has roughness data and radar backscatter (σ^0) for blocky silicic lava flows and a rock avalanche been computed (*Bulmer and Campbell,* 1999; *Bulmer et al.,* 2001). The lack of detailed topographic data for blocky landslides and lava flows has also meant that the link between their roughness and radar backscatter (σ^0) has remained elusive. This has resulted in difficulties in using radar data to distinguish between rock avalanches and lava flows (e.g. *Bulmer and Wilson,* 1999). At C-band wavelengths (ERS and Radarsat) it is not possible to discriminate between a'a lava textures and blocky lava flows or a rock avalanche based upon σ^0 values alone. Geomorphic features such as blocky landslides will only be identified in longer wavelength data or through morphological signatures.

Preparedness (Monitoring Warning, Prediction)

Disaster preparedness involves temporal prediction and warning, and monitoring once a landslide is taking place. Monitoring landslides can either be done from in-situ measurements, with the help of EO data, or a combination of the two. Challenging components of monitoring landslides include characterizing the time of a landslide occurrence, its velocity and its acceleration. These parameters may be quantified by real-time, in-situ monitoring systems, and with EO InSAR data.

In-situ monitoring systems

A real-time monitoring system using instruments selected according to the characteristics of the soil mass, and placed where the earliest movement is estimated to occur, may represent a powerful tool to produce both local and remote alerts (e.g. Angeli et al., 1994) An efficient monitoring system must ensure safe conditions for the operators and provide the greatest amount of data on the dynamics of the sliding mass.

An example of a real-time monitoring system is the "*Early warning monitoring system*", developed by Aquater, Italy. This monitoring system uses National Instrument LabView software and an analogue/digital (A/D) converter with an internal processor to collect data from a laser diastimeter, seismic detectors (geophones), pressure transducer, and rainfall meter. Alerts are automatically activated when a sensor measures variations, which exceed the fixed threshold limits.

The data that the "*Early warning monitoring system*" collects from the instrumented landslide include

- relative movements recorded by a laser diastimeter
- vibrations (intensity and frequency) from geophones
- groundwater pressures changes recorded from pressure transducers
- rainfall (as total amount and intensity) recorded by rainfall meters

In the case of a landslide occurrence, both local and remote warning signals are activated by the system at the same time allowing emergency measures to be taken. Local alarms may consist of lights and sirens; operators can be alerted directly from the local monitoring station modem; and a web site can display real-time data.

InSAR

Interferometric synthetic aperture radar (InSAR) can be applied for measuring displacements at the Earth's surface with very high accuracy and for topographic mapping. Both capabilities are of high relevance for landslide hazard assessment. Possibilities and constraints of spaceborne SAR for these applications are briefly reviewed.

In a SAR image the location of a target is represented in a two-dimensional coordinate system, with one axis in flight direction (along-track) and the other axis cross-track (slant range), in which the target position (distance) is measured by the round trip travel time from the SAR antenna to the target and back. Because the across-track position represents a range measurement, the SAR image is distorted in this direction. Steep slopes facing in direction of the antenna appear shortened or are affected by layover, which often inhibits the interferometric analysis on these slopes.

An interferometric image represents the phase difference between the reflected signal in two SAR images obtained from similar positions in space (Hanssen, 2001; Massonet and Feigl, 1998; Rosen et al., 2000). In case of spaceborne SAR the images are acquired from repeat pass orbits. For the European ERS, for example, the standard orbital repeat interval is 35 days, for the Canadian Radarsat it is 24 days. The phase differences between two repeat-pass images result from topography and from changes in the line-of-sight distance (range) to the radar due to displacement of the surface or change in the atmospheric propagation path length. For a non-moving target the phase differences can be converted into a digital elevation map if very precise satellite orbit data are available. Effects of noise due to changes of atmospheric propagation between various images can be strongly reduced by combined processing of several interferometric image pairs with different baselines (multi-baseline interferometry) (Ferretti et al., 1999).

For motion mapping by means of InSAR it is necessary to separate the motion-related and the topographic phase contributions. This can be done by differential processing using two interferograms of different time periods calculated from two or three images if the motion was constant in time. If the motion is slow, the topographic phase can be taken directly from an interferogram of a short time span (e.g. the one-day time span of the Tandem Phase, when ERS-1 and ERS-2 operated simultaneously).

There are two important constraints for the application of InSAR to slope motion monitoring: (1) InSAR measures only displacements in slant range, the component of the velocity vector in flight direction cannot be measured. (2) InSAR can only map the motion at characteristic temporal and spatial scales (Massonet and Feigl, 1998), related to the spatial resolution of the sensor and the repeat interval of imaging. Typical scales for ERS interferometry application to landslide movements are millimeters to centimeters per month (with 35-day repeat-pass images) down to millimeters to centimeters per year (with approximately annual time spans). Faster landslides could only be studied during special orbital repeat configurations of ERS in previous years (Fruneau and others, 1996), such as the Tandem Phase or the 3-day repeat cycle during the Commissioning Phase and the Ice Phase of ERS-1 during a few months of 1992, 1993 and 1994. With the resolution of ERS (9.6 m in slant range, 6.5 m across track, 5.6 cm wavelength) the minimum horizontal dimension of a landslide for area-extended interferometric analysis, which can be applied with a single image pair, is about two-hundred meters across- and along-track. Future SARs with higher resolution (Radarsat-2) will enable the mapping of smaller slides. With the Permanent Scatterer Technique the movement of small objects (down to about one square meter) can be monitored, as discussed below.

A precondition for the generation of an interferogram is coherence, which means that the phase of the reflected wave at the surface remains the same in the two SAR images. The loss of coherence (decorrelation) is the main problem for interferometric analysis over long time spans, as required for mapping of very slow movements. Whereas the signal of densely vegetated areas decorrelates rapidly, the phase of the radar beam reflected from surfaces, which are sparsely vegetated or unvegetated often remain stable over years. This has been utilized for mapping very slow slope movements in high Alpine terrain (Rott et al., 1999; Rott et al., 2000).

Motion analysis in vegetated areas is only possible if a few stable objects (usually man-made constructions such as houses, roads etc.) are located within these areas. Using long temporal series of interferometric SAR images (typically about 30 or more repeat pass images over several years) objects with stable backscattering phase are determined by statistical analysis. Only some of the man-made objects reveal long-term phase stability. The analysis of the SAR time series with the Permanent Scatterer Technique (Ferretti et al., 2000; 2001) enables the detection of very small movements of individual objects (e.g. single houses). A certain number density of stable objects (at least about 5 per km2) is needed to enable accurate correction of atmospheric phase contributions. This method has been applied to map subsidence in urban and rural areas in various countries.

The future availability of spaceborne InSAR data for slope motion monitoring is not yet clear. The European ERS SAR is a useful system for repeat-pass SAR interferometry because of the high stability of the sensor, good orbit maintenance and the fixed operation mode. However, a system failure that occurred on ERS-2 January 17 2001 has resulted in the orbit deadband being relaxed from +/- 1 km to +/- 5 km. As a result interferometry can only be performed at few random occasions. The European follow-on sensor ASAR on board the ENVISAT, as well as other planned SARs, provide many different operation modes, which will reduce the availability of repeat pass interferometric data. On the other hand, the higher spatial resolution of some of these sensors would be of interest for mapping also small slides. The important contributions of InSAR to hazard management and to a range of other environmental monitoring tasks would justify a long-term SAR mission optimized for InSAR applications.

Due to the typical SAR repeat orbits of the order of 25 to 35 days, InSAR is mainly suitable for monitoring very slow movements of slopes and individual objects, and for mapping of subsidence. Thus it is able to fulfil specific information needs for landslide monitoring, complementary to other information sources. The main advantage over conventional techniques is the possibility of very precise displacement measurements over large areas at reasonable costs, thus being an excellent tool for reconnaissance.

Landslide mitigation

Landslide mitigation comprises the following activities: hazard, vulnerability, and risk assessment, restrictive zoning, and protective engineering solutions. Slope instability hazard zonation or assessment is defined as the mapping of areas with an equal probability of occurrence of landslides within a specified period of time. A landslide hazard zonation consists of two different aspects, the assessment of the susceptibility of the terrain for a slope failure and the determination of the probability that a triggering even occurs.

The essential steps to be followed in landslide hazard zonation are:

- Mapping the landslide distribution based on type, activity, dimensions, etc.
- Mapping and analyzing the most relevant terrain parameters related to the occurrence of landslides.
- Assigning weights to the individual causative factors, the formulation of decision rules and the designation of landslide susceptibility class.

The development of a clear hierarchical methodology in hazard zonation is a necessary condition to obtain an acceptable cost/benefit ratio and to ensure its practical applicability. The working scale for a slope instability analysis is determined by the requirements of the user for whom the survey is executed. Planners and engineers use the following examples of scales:

- National scale (< 1:1000000) provides a general inventory of problem areas for an entire country, which can be used to inform national policy makers and the general public.
- Regional scale (1:100000 - 1:500000) is used in the early phases of regional development projects to evaluate possible constraints, due to instability, in the development of large engineering projects and regional development plans.
- Medium scale (1:25000 - 1:50000) is used for the determination of hazard zones in areas affected by large engineering structures, roads and urbanization plans.
- Large scale (1:5000 - 1:15000) is used at the level of site investigations prior to the design phase of engineering works.

EO information requirements for landslide mitigation

Potentially unstable slopes and landslides are most often local scale features, even though they can occur in great numbers over a wide area (especially when triggered by a large earthquake or a very intense and/or prolonged storm). This and the limited areal extent of many damaging or socio-economically significant mass movements (often as little as few tens of square meters or less), imply that satellite observation and monitoring will require much greater spatial and vertical resolution with respect to that used in the study of other natural disasters such as floods, earthquakes, volcanic eruptions.

More detailed scales (1:5000 or better) are also required during the site investigations aimed at providing reliable information for designing engineering control works needed to prevent or repair slope failures (Turner and Schuster 1996). In order to be used profitably for slope stability analyses and for planning subsurface investigations, which typically precede the actual engineering construction phase, the acquired detailed information will also need to be quantitative, where possible. In general, the greatest possible (or economically justified) level of detail may be warranted. This will be particularly the case in urban or per-urban settings where public safety is the principal issue, or where the socio-economic consequences of potential landslide damage might be severe. Therefore, the scales required during the design of slopes are often larger than 1:2000, and the most commonly used scales may vary from 1:1000 to 1:500. In some cases, even more detailed scales are utilised. This level of detail would imply a sub-meter pixel spatial resolution of remotely sensed data. Similarly, the altimetric resolution would need to be close to 0,5 m. Therefore, the practical or operational use of the currently available EO data in engineering geology site-specific landslide investigations is considerably limited (Wasowski and Gostelow, 1999). The improved resolution of the planned future sensors (3 m or better pixel resolution), however, should provide information sufficiently detailed for assessing the feasibility of slope engineering projects and for defining some preliminary design characteristics. Various methods have been used to produce landslide inventory maps. These maps are produced from the interpretation of stereo aerial photographs, satellite images, ground surveys, and historical occurrences of landslides. The final product gives the spatial distribution of mass movements, represented either at scale or as points. When multi-temporal airborne or satellite image analysis is included the inventory maps show landslide activity.

There are two aspects of EO data that are important for landslide mitigation. First of all, it has been shown that multi-temporal EO data can be used to determine the changes in landslide distribution, and as such are useful to produce landslide inventory maps. Second, EO data can be used to map factors that are related to the occurrence of landslides, such as lithology, faults, slope, vegetation and land use. The temporal changes in these factors can also be mapped, which can be used within a GIS in combination with a landslide inventory map for landslide hazard assessment.

Current landslide inventory maps are not standardized around the world. They are published at different scales with various levels of details. These maps usually include information on the classification of the landslide type, their location, as well as the geomorphic and slope characteristics. In some cases, active and dormant landslides are distinguished. In other cases, the information is included on geological and soil degradation maps.

For the evaluation of the suitability of remote sensing images for landslide inventory mapping the size of individual slope failures in relation to the ground resolution cell is of crucial importance. Although sizes of landslides vary enormously according to the type of slope failure, some useful information can be found in literature. The total map area for a failure of 42000 m^2 corresponds with 20 x 20 pixels on a SPOT Pan image and 10 x 10 pixels on SPOT multispectral images. This would be sufficient to identify a landslide displaying a high contrast, but it is insufficient for a proper analysis of the elements pertaining to the failure to establish characteristics and type of landslide. It is believed that if 1:15.000 is the most appropriate scale, then, 1:25.000 should be considered as the smallest scale to analyze slope instability phenomena on aerial photographs. Using smaller scales a slope failure may be recognized as such, if size and contrast are sufficiently large. However, the amount of analytical information, enabling the interpreter to make conclusions on type and causes of the landslide, will be very limited at scales smaller than 1:25.000. For this reason, 3-meter stereo images will be most useful for detail interpretation.

Currently, air photos are used extensively to produce landslide inventory maps, because they allow features demonstrating slope movement that range from small terracettes, indicating soil creep to large landslides to be resolved. Current research has shown that high-resolution stereo SAR and optical images, combined with topographic and geological information have assisted in the production of landslide inventory maps. The multi-incidence, stereo and high-resolution capabilities of RADARSAT are particularly useful for landslide inventory maps. High-resolution systems such as IKONOS, IRS and the stereo capability of SPOT 4 are useful for landslide recognition and related land use mapping. Other planned high-resolution stereo systems such as ENVISAT and RADARSAT-2, and ALOS will be useful to map landslide features.

To facilitate the use EO data for landslide inventory maps more research needs to be done in the following areas in the short term:

- High resolution (<8m) remote sensing data needs to be easily integrated with existing information. This task is particularly challenging in high relief slopes where most landslides occur.
- Current landslide interpretation, data fusion and InSAR techniques needs to be tested in different topographic and geological environments.
- Standardized landslide inventory mapping procedures using high resolution RS data as an image base needs to be developed. This is possible at a scale of 1:50000 using current techniques.
- Low-cost DDTM (= differentiated DTM) can be generated from multi-temporal aerial photographs in order to assess landslide vulnerability.

III. RESPONSE

Disaster response comprises the rapid damage assessment, and relief operations, once the disaster has occurred. Currently, damage assessment is done using aerial photography, videography and ground checks. In order to be able to use EO data for landslide damage assessment, two criteria should be met: High temporal and high spatial resolution (ca 3-10m stereo) is essential for landslide damage assessment and relief efforts. Images taken at the time of disaster or days after the event similar to other geohazards –earthquake and volcanoes – is a requirement to support relief efforts. This will be satisfied, in part, by existing and planned high resolution, stereo optical and SAR systems. In cases where the damage is extensive, either as a single large event, or many small events covering a large area, there is a need for high-resolution images (ca 3-10m), before and after event. This can be used to supplement airborne and ground techniques for local and regional damage assessment. Guidelines for a landslide hazard emergency response scenario are presented at the end of this report. It is intended that this will help to facilitate the efforts of space agencies to acquire appropriate data in order to achieve timely delivery of image maps for relief agencies.

IV. RESEARCH, CHALLENGES AND LIMITATIONS ASSOCIATED WITH EO DATA

The difficulties associated with interpretation of EO data can require a high level of user knowledge in remote sensing systems. Characterizing form, size, causative and triggering factors, pre-monitory signs, mechanisms, post-failure evolution will require both ground-truth knowledge and advanced technical skills in remote sensing processing. Although any InSAR sensed deformation is potentially of interest to an engineering geologist or geotechnical engineer, in the case of landslides or unstable slope areas, a change detection in both vertical and horizontal distances is needed to evaluate landslide mechanisms (the monitoring of a horizontal component of movement is often critical for hazard assessments). Furthermore, some other phenomena such as subsidence (eg. caused by natural processes such as compaction, thawing, or man-made), settlement or subsidence of engineering structures, (eg. caused by compression), shrink and swell of some geological materials, need to be taken into account to correctly interpret the significance of the ground deformation one might be detecting from EO data. The additional specific aspects of the geological context to be considered in the EO data interpretation include (Wasowski and Gostelow (1999):

- three phases of landslide movements (pre-failure, during failure and post-failure)
- importance of gravity or continuous creep distinction
- weathering and shallow seasonal creep

It follows that, in general, the information obtained from InSAR (or other EO) methods will need to be correlated with ground data and detailed survey controls in order to be correctly evaluated and to provide a reliable relevant information to a disaster management community or to engineering geologists and geotechnical engineers. In short, at present the InSAR methods could be viewed as the complementary data source with respect to those acquired through ground based observations and in-situ surveying. They will be especially attractive where no other data sources are available by providing initial (potentially wide-area) assessments of ground deformation susceptibility.

The limitations and benefits of InSAR data processing techniques in terms of the time and cost requirements is very difficult to assess at this time, with respect to in-situ monitoring operations and surveying.

CEOS Demonstration Sites

Given the research gaps outlined above, the Landslide Hazard team plans to concentrate its efforts on 3 test areas with different geological and terrain conditions. The choice of the sites is based on (1) geological diversity; (2) the types of landslides, (3) current threat to populated areas and infrastructure, and (4) existing work conducted by the current Landslide team. Earthquakes, excessive rainfall, and volcanic events are the triggers of the landslides, and this allows the CEOS landslide team to work more closely with the other working groups on earthquake, volcanic and flood hazards. The focus, however, will be to evaluate current and future satellite high-resolution, stereo and interferometric systems, and to develop standardized tools to characterize and monitor unstable slopes in the following areas.

Fraser Valley Landslides: Canadian Cordillera

The Fraser valley in the Canadian Cordillera, is one of the most strategically important transportation corridors in Canada. Almost all the transportation lifelines that link the prairie provinces with metropolitan Vancouver utilize this corridor. Thirty-five large landslides ranging in size from at least 1 million to more than 500 million cubic metres have been identified in the lower Fraser Valley. Recently, landslides have caused serious damage to the major transportation links. In the spring of 1997, landslides have caused the derailment of the CN railway resulting in two deaths and 20 million dollars of damage. In 1965, a large rock avalanche (48 x 10^6 m3) known as the Hope slide, occurred 160 km east of Vancouver. The slide triggered by two small earthquakes (M) 3.2 and 3.1, buried three vehicles and claimed four lives. The causes of landslides in the area include the weakening of failure planes in carbonate rocks, solution erosion, seismic shaking, the presence of clay infilling along discontinuities, steep slopes, excessive precipitation and deforestation. Savigny (1993) identified three types of slides in the lower Fraser Valley. These include (1) slump and earth flow of surficial materials, mainly glacial drift; (2) rock slide with slide scars and multiple scarps and (3) rock slumps with several arcuate scarps. These slides mainly occur along the contact between plutons and metamorphic pendants and are associated with regional north trending thrust and strike slip faults and lineaments. Singhroy et al (1998) used differential airborne interferometry and high resolution (8m) stereo RADARSAT images to map detail slope geomprphology for landslide inventory in the region. Repeat pass interferometry techniques on the vegetation free slopes will be used to monitor motion on unstable slopes.

The Corniglio Landslide: Northern Apennines, Italy

The Corniglio landslide in the Emilia-Romangna Apennine Mts. in northern Italy (44°28' N - 10°05' E) is an active large complex retrogressive landslide (length 3080 m, max. width 1120 m, depth between 30 and 120 m) which underwent recent reactivation in 1994 and 1996 and 2001. Abundant rainfall and minor seismic events accompany reactivation of this type. Field inspections in October 2000 and May 2001 indicate gradual sliding at the head scarp and lower toe regions. The rate of movement during re-activation periods varies from centimeter to several meters per day. Average velocity (1994-96 period) for the middle-lower part of the slide is below 1 m/day. Average daily rates of collateral deformations is < 1mm/day in the town of Corniglio (44.28 N, 10.05 E). The lithology consists of sandstone, limestone, and argillite clasts mixed in fine-grained materials (silty-sandy clay), derived from tectonically deformed “flysch” (turbidite) units. The average slope is <10° in the lower 3/4 of the slide (flow portion); 23° in the upper-most part. The middle-upper part of the slide is bare with grassland, while the lower 1/3 (toe) is sparsely vegetated with trees. Because of the spare vegetation differential InSAR techniques will be used to monitor motion at this site. The buildings of the town will be used as corner reflectors. Continuous monitoring by 15 automated inclinometers, demonstrates that the slide is still moving slowly on a 10 degrees clay slope. Local topographic network and 10 piezometers will provide additional field monitoring data.

Itaya Landslide: Japan

The Itaya landslide is an active silde in Yamagata Prefecture, northern Japan. The landslide is located on the northern slope of Azumayama Volcano. Geologically, the surface of the landslide and its surrounding areas is covered by debris flow deposits composed of andesitic volcanic rocks Interferograms constructed from JERS-1 SAR provided a model of active movement of sub-blocks along slip planes during periods of heavy precipitation (Kimura and Yamaguchi 2000). Stereo RADARSAT images are currently being used to characterize the geomorphic features of the slide. The landslide hazard team will conduct evaluation of future Japanese ALOS data

V. SUMMARY

Our challenge is to recognize and interpret the detailed geomorphic characteristics of large and small landslides, and determine whether or not failure is likely to occur. This has not been fully explored to date from current EO data.

- The role of EO data for landslide hazard assessment will increase as more useful techniques are developed.

- Recent results have shown that more use can be made from current high resolution stereo SAR and optical images to produce more standardized landslide inventory maps which will assist hazard planning.
- The availability of less than 3-meter resolution stereo images from planned SAR and optical systems will increase the geomorphic information on slopes, and therefore produce more reliable landslide inventory and risk maps.
- Landslide prediction will remain complex and difficult even with ground techniques.
- GIS and RS techniques will remain a regional analysis tool.
- Detail slope and motion maps produced from InSAR techniques can assist in more accurate slope stability studies. When the conditions are correct, SAR interferometry is a useful tool for detecting and monitoring mass movement and thus is able to contribute to the assessment and mitigation of landslide hazards.

Guidelines for Landslide Hazard Emergency Response Scenario

Request for assistance would be triggered if a landslide was a threat to life, and or threatened or caused safety or damage to property and infrastructure

Obtain background information		Check if Considered
1.	Location of the landslide (latitude, longitude, possibly GPS info)	
2.	Date and Time of the landslide	
3.	Responsible Search and Rescue Agency (s)	
4.	Contact information for all involved agencies (support agencies, on-scene commander, etc.)	
4.	Location of nearby populated areas and infrastructure such as energy and transportation routes	
5.	Geological (terrain, lithology, structure and seismic), topographic land use/land cover and other risk hazard maps – at scales less than 1: 50,000 if available	
6.	Meteorological data particularly rainfall information before, during and after the event	
7.	Archival, stereo air photos at scale from 1: 5000-50000, and other remote sensing data such as Landsat, SPOT IRS, RADARSAT, ERS , JERS, and Russian high resolution optical data Space agencies should produce " thumbnails of archival images to ensure high quality comparisons and data fusion	
Priorities for image planning		
1.	A. Characterize landslide areas, and assess damage require high to medium resolution (3-10m) cloud free stereo and single images. For example RADARSAT: Fine beam modes F1-5, and RADARSAT Stereo (F1, F5) (F2,F5) (F3, F5) with same look directions – ascending / ascending or descending /descending IKONOS: 4 m. multi spectral: 1m. panchromatic IRS: 5.8m SPOT: 10m stereo and panchromatic B. Monitor motion soon after the slide resulting from seismic aftershocks requires InSAR imagery. For example:- 1 InSAR pair- ERS1&2 ENVISAT, RADARSAT, ALOS) or most ideally 2 InSAR pairs within the first month after the event.	

Value Added Products in support of relief effort (ideally within 2 weeks after the event)

The following value added products should be available for a comprehensive relief effort:

To assess ground/ slope instability:

- Less than 1: 20 000 interpreted image maps (digital and print) with detail geomorphological and geological characterization and interpretation of slide mechanics
- InSAR coherent maps with annotated interpretation for general use

To assess damage:

- Thematic maps at scales less than 1:20000. showing damaged areas such as buildings, infrastructure and resources (forestry etc).
- Change detection image maps using current and archival images with simple legend for general use.

Data delivery :

An Internet transfer system should be established to transfer all images and value added products to relief agencies and participating interpretation agencies. In order for agencies to most effectively work together, all parties should have the same set of state- of art information available as quickly as possible.

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References

Alexander, D. Natural Disasters. Chapman and Hall, New York, pp 621.

Angeli, M-G., P Gasparetto, R.M. Menotti, A. Pasuto, and S. Silvano. 1994. A system of monitoring and warning in a complex landslide in Northeastern Italy. Landslide News 8: 12-15.

Bulmer, M.H., Murphy, W., Petley, D., Mantovani, F., Keefer, D., and Jibson, R. Operational use of InSAR for landslide studies: Experiences from Black Ven landslide, Dorset 2001. Submitted to Adv. Space Res.

Bulmer, M.H., B.A., Campbell, and J. Byrnes. 2001. Field Studies and Radar Remote Sensing of Silicic lava flows. Lunar and Planet. Sci. Conf., XXXI, 1850.

Bulmer, M.H., and Wilson J.B., 1999. Comparison of Stellate Volcanoes on Earth's Seafloor with Stellate Domes on Venus using Side Scan Sonar and Magellan Synthetic Aperture Radar, *Earth and Planet. Sci. Lett.* 171, 277-287.

Bulmer, M.H., and B.A., Campbell, 1999. Topographic data for a silicic lava flow – A planetary analog, Lunar and Planet. Sci. Conf., XXX, 1446-1447.

Campbell, B.A. and M.K. Shepard, 1996. Lava flow surface roughness and depolarized radar scattering, J. Geophys. Res., 101:18,941-18,951.

Carnec, C., Massonet, D., and King, C. 1996. Two examples of the use of SAR interferometry on displacement fields of small extent. Geophys. Res. Letts., 23 (24): 3579-3582.

Cruden, D.M. 1980. A large landslide on Mars: Discussion and reply, *G.S.A. Bull.,* 91, 63.

Evans, S. G. and Savigny K.W. 1994. Landslide in the Vancouver –Fraser Valley-Whistler region. (In) *Geology and Geological Hazards of the Vancouver Region, Southwestern British Columbia.* (ed) J.W. H. Monger; Geological Survey of Canada, Bulletin 481, p 251-286

Ferretti, A., C. Prati and F. Rocca, 2001. Permanent scatterers in SAR interferometry. *IEEE Trans. Geosc. Rem. Sens., 39,* 8-20.

Ferretti, A., C. Prati and F. Rocca, 2000. Nonlinear subsidence rate estimation using permanent scatterers in differential SAR interferometry. *IEEE Trans. Geosc. Rem. Sens., 38,* 2202-2212.

Ferretti, A., C. Prati and F. Rocca, 1999. Multibaseline InSAR DEM reconstruction: The wavelet approach. *IEEE Trans. Geosc. Rem. Sens., 37,* 705-715.

Ferretti A, Prati C, Rocca F.1999. Permanent scatteres in SAR interferometry. *Proc. IGARSS'99* Conference, Hamburg 3p.

Ferretti A., C. Prati, F. Rocca, 1999a Monitoring Terrain Deformations Using Multi-Temporal SAR Images *Proc. of FRINGE'99*, Liege, Belgium

Fruneau, B., Achache, J., and Delacourt, C. 1996. Observations and modelling of the Saint-Etienne-de-Tinee landslide using SAR interferometry. Tectonophys. 265: 181-190.

Fruneau, B., Delacourt C., and Achache, J., 1996. Observation and Modelling of the Saint-Etienne-de-Tin´ ee Landslide Using SAR Interferometry, *Proc. of FRINGE'96*, Zurich, Switzerland

Garvin, J. B., and J. J. Frawley, Global vertical roughness of Mars from Mars Orbiter Laser Altimeter pulse-width measurements, *Lunar Planet. Sci.,* 31, abstract, 2000.

Hanssen, R.F., Radar Interferometry, 2001. Kluwer Academic Publ. Dordrecht etc., 308 pp.

Johnson, A.M. 1984. Debris flow, In: Bunsden , D., and Prior, D.B., (eds.) Slope Instability, John Wiley and Sons, New York, 257-361.

Kabill, W.B, Wright, C.W., Swift., R.N and 8 others. 2000. Airborne laser mapping of

Assateague National Seashore Beach. Photogrammetric Engineering and Remote Sensing, 66, 1, 65-71.

Keefer, D.1984. Landslides caused by earthquakes. *Geological Society of America Bulletin* Vol.95, p406-421

Keefer, D.1994 The importance of earthquake-induced landslides to long-term slope erosion and slope failure hazards in seismically active regions. *Geom. Vol* 10 p265-84

Kierch, G. A., 1965, "The Vaiont Reservoir Disaster," California Division of Mines and Geology, Mineral Information Service, Vol. 18, No. 7, p 129-138

Kimura, H., and Y Yamaguchi. 2000.Detection of Landslide areas Using Radar Interferometry. *Photogram Eng. and Remote Sensing* Vol. 66, No.3, p337-344.

Lillesand, T.M., and R.W., Kiefer, 1987. Remote Sensing and Image Interpretation. John Wiley and Sons, New York, p321.

Massonnet, D., Vadon, H., and Rossi, M. 1996. Reduction in the need for phase unwrapping in the radar interferometry. IEEE Trans. Geosci. Rem. Sens., 34 (2): 489-497.

Massonnet, D., and Feigl, K.L. 1998. Radar interferometry and its application to changes in the Earth's surface. Rev. of Geophys., 36 (4): 441-500.

McKean J, Buechel S, Gaydos L. 1991 Remote sensing and landslide hazard assessment. *Photogrammetric Engineering and Remote Sensing*, 57, p1185-1193

Plaut, J., 1993. Stereo Imaging. In. Guide to Magellan Image Interpretation (J.P., Ford and 7 others), NASA JPL Publication 93-24, pp33-43.

Refice, A., Bovenga. F, Wasowski. J, and L. Guerriero. 2000 Use of InSAR Data for Landslide Monitoring: A Case Study from Southern Italy. IGARSS 2000, Hawaii. 3p

Rosen P.A. et al., 2000. Synthetic Aperture Radar Interferometry. *Proceedings of the IEEE, 88(3)*, 333-385.

Rott, H., and A. Siegel, 1999. Analysis of Mass Movements in Alpine Terrain by Means of SAR Interferometry, *Proc. of IGARSS'99*, Hamburg, 3p

Rott H., B. Scheuchl, A. Siegel and B. Grasemann, 1999. Monitoring very slow slope movements by means of SAR interferometry: a case study from a mass waste above a reservoir in the Ötztal Alps, Austria. *Geophysical Res. Letters 26*, 1629-1632.

Rott H., C. Mayer and A. Siegel, 2000. On the operational potential of SAR interferometry for monitoring mass movements in Alpine areas. *Proc. of the 3rd European Conference on Synthetic Aperture Radar (EUSAR 2000)*, Munich, 23-25 May 2000, 43-46.

Savigny, W.K., 1993. Engineering Geology of Large Landslides in the Lower Fraser River Valley Transportation Corridor, Southwestern Canadian Cordillera, *GAC Special Volume,* Landslide Hazard in the Canadian Cordillera. 30p.

Shaller, P.J., 1991. Analysis and implications of large martian and terrestrial landslides, PhD thesis, Calif. Inst. Tech., pp586.

Shepard, M.K., R.A., Brackett, and R.E., Arvidson, 1995. Self-affine (fractal) topography: Surface parameterization and radar scattering, J. Geophys. Res., 100, 11,709-11,718.

Shreve, R.L. 1966. Sherman landslide, Alaska, Science, 154: 1639-1643.

Singhroy, V., Mattar, K.E., and Gray, A.L., 1998. Landslide characteristics in Canada using interferometric SAR and combined SAR and TM images. Adv. Space Res., 3, 465-476.

Singhroy, V.and K. Mattar. 2000. SAR image techniques for mapping areas of landslides. *ISPRS 2000. Proceedings.* Amsterdam, p1395-1402

Soeters R, van Westen CJ 1996 Slope instability recognition, analysis, and zonation. In Landslides. Investigation and mitigation, ed A. K. Turner, R. L. Schuster.

Transportation Research Board Spec. Rep. 247. Nat. Academy Press, 673p

Steinbrugge, K.V. ,1982, “Earthquakes, Volcanoes, and Tsunamis – An Anatomy of Hazards,” pp. 85-87, Skandia America Group, 280 Park Avenue, New York, N.Y. 10017, USA, 392p.

Turner A. K. and Schuster R. L. (eds.) 1996, “Landslides. Investigation and mitigation”, *Transportation Research Board Special Report 247*, National Academy Press, 673 pp.

Varnes, D.J. 1974. The logic of geologic maps, with reference to their interpretation for engineering purposes. U.S. Geol. Surv. Prof. Pap., 837.

Wasowski, J. and P. Gostelow, 1999. Engineering geology landslide investigations and SAR interferometry, *Proc. of FRINGE’99*, Liege, Belgium.

Wasowski J. and Gostelow P. 1999, “Engineering geology landslide investigations and SAR Interferometry”, *Proceedings of FRINGE’99*, Liege, Belgium, http://www.esa.int/fringe99