Traditional and Innovative Techniques for Landslide Monitoring: dissertation on design criteria

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Zusammenfassung

Die messtechnische Überwachung von Hangbewegungen stellt für Geologen und Ingenieure einen hocheffektive Ansatz zur Beurteilung, Prognose und ggf. Beeinflussung der Stabilitätseigenschaften solcher Massenbewegungen dar. Dennoch stellt die Identifizierung der maßgebenden Parameter und die Wahl der geeigneten Messverfahren angesichts der großen Variabilität der geomorphologischen, geologischen, geomechanischen und geotechnischen Eigenschaften eine große Herausforderung für den Anwender dar. Bis vor wenigen Jahren stellten "direkte", also in-situ installierte Messgeräte, die einzigen überhaupt verfügbaren Verfahren dar. Diese Verfahren waren – und sind – in der Lage, Parameter wie Verformungen, Relativverschiebungen, Neigungsveränderungen, Wasserspiegel, Porenwasserdruck. etc. sowohl an der Oberfläche, als auch im Untergrund zu erfassen. Messgeräte, wie Extensometer, Inklinometer, Porenwasserdruckgeber, usw. sind nach wie vor wesentliche und allgemein anerkannte Werkzeuge für die präzise Erfassung von Punktinformationen und darauf aufbauende Stabilitätsbetrachtungen und –prognosen.

Während der letzten Jahre sind jedoch – neben einer durchaus erwähnenswerten Weiterenzwicklung der traditionellen "direkten" Verfahren – auch neue Ansätze entwickelt worden, die auf der Fernerkundung von Oberflächenbewegungen basieren und neue, faszinierende Möglichkeiten für die Überwachung von Hangbewegungen erschließen. Der vorliegende Beitrag beschäftigt sich mit den am weitesten verbreiteten Fernerkundungsverfahren: DGPS (Differential Global Positioning System), geodätischen Totalstationen, luftgestützter und terrestrischer Photogrammetrie, Laserscanning sowie terrestrischem und satellitenbasiertem SAR. Es sollen zudem auf Basis der gewonnenen Erfahrungen Planungskriterien für die Überwachung von Hangbewegungen vorgestellt werden, die die zahlreichen Methoden, die spezifischen Probleme (kritische Beobachtungspunkte, erforderliche Messgenauigkeit, Veränderungsraten, Überwachungsdauer, Oberflächenmessung / Tiefenmessung, Messfrequenz, Umwelt- und Rahmenbedingungen, Projektsituation bzw. Organisationsstruktur des Kunden) sowie wirtschaftliche Aspekte in Betracht ziehen. Durch die spezifischen Erfahrungen der beiden Autoren in beiden Bereichen – direkten und indirekten Verfahren – kann dabei ein zusammenfassender Überblick über mögliche Lösungsansätze gegeben werden.

Schlüsselworte: Hangbewegungen, Monitoring, Messungen, in-situ-Verfahren, remote-Verfahren, Planungskriterien, Eignung, Risiken, Alarmierung, Frühwarnung, Datenübertragung, Datenverarbeitung

Abstract

Monitoring of landslide parameters is a powerful weapon in the hands of geologists and engineers for the assessment and control of stability conditions of a slope and to predict its future evolution. However, due to the large variety of geomorphological, geological, geomechanical and geotechnical conditions the identification of the most suitable parameters and of the best instrumental solutions is a big challenge. Until few years ago "contact" equipments have been the only available for landslide monitoring. They were, and they are still, able to measure both surface or in depth parameters such as strain, displacement, inclination, water level, pore pressure etc.. These techniques, such as extensometers, inclinometers, piezometers etc, are essential and widely accepted tools able to provide accurate measurements at specific points thus enabling stability evaluation and forecast analysis.

Over the last years, together with a relevant improvement of traditional "contact", a new approach to landslide monitoring based on remote measurement of surface ground movements is developed, thus providing new interesting opportunities to landslide monitoring matter. The paper deals with the most common remote techniques: DGPS (Differential Global Positioning System), Topographic Total Stations, Aerial and Terrestrial Photogrammetry, Laser scanner, Terrestrial and Satellite SAR and aims at providing design "criteria" for landslide monitoring by looking to the wide spectrum of available techniques in relation to the specific landslide problems (critical monitoring points, requested accuracy, rate of change of the monitored quantities, duration of the monitoring period, surface or depth measurements, measuring frequency, boundary and environmental conditions, site situations and customers organization) we dealt with, and to the specific monitoring purpose without neglecting the economic factor.

It is worth to note that both contact and remote techniques will be considered thanks to the mutual expertise of the authors, thus provide a comprehensive overview of available solutions.

Keywords: Landslide, monitoring, measurement, contact measurement, remote measurement, design criteria, suitability, risk, alarm, early warning, data transmission, data processing

1 Introduction

Over the last 20 years a strong increase of available techniques for the monitoring of landslides and ground instability processes has been observed (Dunnicliff, 1989; Mazzanti, 2012). Hence, several opportunities are now available to monitor landslides processes acting on the earth surface. Moreover, some of these innovative techniques are opening new frontiers in the monitoring and analysis of landslides. For example, by using satellite InSAR (Hansenn, 2001) historical displacements (since 1992) can be retrieved, thus changing a paradigm of the traditional monitoring, i.e. the monitoring can be performed only after the installation of a sensor. The availability of several new monitoring opportunities lead engineers and geologists to the consciousness that structural engineering slopes stabilization are not the only solutions for the reduction of landslide risk. It has been demonstrated that a suitable monitoring project may support the design of a stabilization project and, when structural interventions are not feasible or not convenient, it can be the final solution for risk mitigation. Several examples of monitoring systems for early warning purposes are available starting from the end of '80 for rainfalls induced debris flows (Keefer et al, 1987; Aleotti, 2004; Badoux et al, 2009; Baum and Godt, 2010; Huggel et al, 2010) rock falls (Clark et al, 1996; Barton and Mc Cosker, 2000; Bernardi et al, 2008; Senfaute et al, 2009) and more extensively for large rockslides and earthflows (Varnes et al, 1996; Froese et al, 2005; Froese and Moreno, 2011; Blikra 2012; Loew et al, 2012a-b) and large landslides related to large construction projects (Bozzano et al, 2008; McFarlan, 2009; Yin et al, 2010; Prestininzi et al, 2012; Bozzano et al, 2013).

The sudden increase of available technologies has not been followed by a suitable development of advanced education and training of technicians and surveyor, thus leading in some cases to overestimated expectations and not satisfactory results. Furthermore, especially for innovative technologies, there is a lack of criteria to be used for both surveyor and designers. Hence, it is necessary a strong effort of the experts to consider the "ground stability monitoring" as a matter requiring advanced knowledge and, especially, dedicated design.

This paper aims to demonstrate the importance of a suitable design before affording a landslide monitoring project and, then, to suggests some preliminary criteria for practitioners and designers. The Author's experience will permit to deal with both traditional geotechnical methods and innovative remote sensing solutions, thus providing exhaustive evaluation on the landslide monitoring matter.

The paper is divided in a first paragraph dedicated to landslides descriptions in a monitoring perspective. The second paragraph will focus mainly on the "monitoring purposes", since they are considered as a key factor in the design of monitoring systems and in the choice of suitable instrumentations. Then, the main features of a monitoring system, with reference to the specific purpose, will be briefly discussed and presented through dedicated examples.

2 Landslide description

Landslides are complex processes characterized by a wide range of features. This is the first aspect to be considered when dealing with landslides.

Landslides can be classified on the basis of several features such as: i) involved material, ii) size; iii) morphological features, iv) age, v) triggering mechanisms, vi) type of movement; vii) velocity etc (Cruden and Varnes, 1996; Hungr et al, 2001). The involved material, the size and the geomorphological features are internal features that control the landslide initiation and propagation, hence, they are fundamental in a landslide characterization. As a matter of fact, based only on these basic geological, geotechnical and geomorphological features a good practitioner can be able to classified and understand a slope movement and, therefore, to design a suitable monitoring system.

The type of movement and the velocity are mainly controlled by the above mentioned geological, geotechnical and geomorphological features, but they are related also to external factors like the age of the process, the triggering and preconditioning factors.

It is noteworthy that the movement is the most evident consequence of a gravity-induced activity of a slope, and the most commonly used parameter for landslide monitoring and prediction purposes.

Two main investigation approaches are commonly used for landslides: a) static investigation; b) temporal monitoring.

Static investigation includes the analysis conventionally performed for deriving geological, geotechnical and geomorphological features of the slopes including, among the others, field survey interpretation, aerial photo interpretation, boreholes, penetrometric tests, geophysical surveys, laboratory tests etc. These standard characterization approaches are necessary to derive the most relevant features of a slope and important to predict its future evolution. However, these information are collected in a specific time (i.e. under invariant conditions), hence, they are not exhaustive for the comprehension of a landslide process.

On the other hand, temporal monitoring includes all the analysis carried out ever time, whose purpose is to measure the modification of predefined parameters over time. This investigation approach is not focused on the comprehension of the temporal mechanical evolution of the landslide process. The most common "monitored" parameters are rainfalls, water table, seismic action, stress, deformation and or displacement. Some of these parameters measure the "causes" which lead to a landslide (e.g. rainfalls, water table, seismic action) while some others measure the "effects" (e.g. deformation, stress, displacement) of a landslide.

Monitoring the causes of a landslide is theoretically the most skilled solution since it could allow, on the basis of specific evolutionary models, to predict the effects and to estimate the future evolution. However, instead of numerous studies, several uncertainties are still present regarding the correlation between causes and effects.

On the other hand, effects (i.e. displacements etc), are most easy to be recognized and to be related to the evolution of a landslide. Furthermore, simple and effective prediction models based on landside displacement temporal evolution are available. For this reason the monitoring of effects is the most used solution.

Apart form above mentioned "standard" features, some other aspects can be considered in the landslide description such as the vegetation coverage, the climatic condition and the geographic location. These features are not so relevant in a traditional landslide characterization but they are very important in view of a monitoring design since they can strongly condition the efficacy of used techniques and instruments.

3 Monitoring Purposes

Landslide monitoring is one of the classical tasks that has always stimulated manufacturers to design new and suitable instruments and service providers to develop new system architectures enabling to withstand the difficult environmental conditions as well as the need for reducing the presence of operators at site.

The approach to the landslide monitoring is strictly related to the purpose of the monitoring which can be summarized in the following five main categories:

- "Investigation" of the slide nature whose aim is to provide a support to the comprehensive knowledge of the landslide features by looking to information regarding its past and present behaviour. Both short and long term monitoring can be effective is carried out under different external conditions. The monitoring of both landslide "causes" and "effects" parameters is fundamental for such a purpose.
- Temporal check (control) whose aims are the improvement of the knowledge of a process and the check of the correspondence between "hypothesized" and real future evolution. The definition of standard protocols of monitoring have to be adopted for the entire monitoring activity which must be performed for a long time. Sometimes, one simple instrument can be used and a single parameter can be monitored (once the most useful is identified) and the data sampling rate is compatible with manual data collection (automatic systems are not necessary).
- Early Warning Systems whose aim in to provide alert and alarm signals to ensure the safety of population and infrastructures. They require a deep geological and geotechnical knowledge of the process, a continuous real time and long term monitoring system with a high data sampling rate (to be calibrated on the basis of the landslide features). Instrument redundancy for cross validation and guarantee of continuous operation are also considered important features of the system which will be connected to intervention plan to respond to the phenomena (i.e. alert dissemination, public awareness and response plans).
- Tests of stabilization engineering works efficacy whose aim is to check the behaviour of a stabilization structure during or after its realization and/or to verify the correctness of the design and implementation of engineering interventions. Periodic monitoring is conventionally used. It is mandatory to start the monitoring before the initiation of engineering works. Instruments with a high accuracy are necessary for such a purpose.
- Safety of working areas whose aim it to guarantee the safety of workers and populations during the most critical phases of engineering works. A continuous and automatic operating monitoring system with a high accuracy and a strong "operational stability" is required. Instrument characterized by a widespread view capability is important and high data sampling rate is required.

Items a. to c. can be assumed as "natural", i.e. they can be related to a natural processes (i.e. a natural slope instability) which can affect the human activities. On the other hand, items d. and e. can be assumed as "anthropic", since they are closely related to human engineering works leading to the modification of a natural environment.

However, the above presented classification have not to be considered in a rigid way. As a matter of fact, in several practical cases more than one purpose is required and, still more, one single landslide can require a shift between one purpose to the other during its history due to its modified conditions.

According to the purpose of the monitoring program, the applicable solutions will be focused on specific aspects as well as technical and technological issues. Of course, a monitoring program could include more than one of the purposes and, therefore, it shall be designed considering the different aspects and assuming a significant degree of flexibility.

4 How to make the choice

Considering the complexity of each landslide monitoring systems, the selection of the most appropriate instruments represents one of the key steps of the whole process.

A correct choice of the technique and of the equipment is necessary to provide useful information to end-users (i.e. persons responsible for decision making) and to optimize the costs.

4.1 Contact *vs* remote technique

Nowadays, aside of the "traditional ones" (inclinometers, piezometers, extensometers, total pressure cells, load cells, rain/snow gauges, temperature gauges, etc..), several new instruments are available such as automatic geodetic stations, digital photogrammetric devices, radar and laser devices. These new instruments, often based on a "remote" operational principle, increase the choices and the monitoring potentialities. A comprehensive overview of traditional equipment can be found in Dunnicliff (1988), while a quick review of remote technologies can be found in Mazzanti (2012).

The remote sensing techniques present the great advantage of covering wide areas and measuring movements in a large number of points with high accuracy; nevertheless they are suitable only for the measure of surface movement.

Together with the obvious advantages, the rapid increase of available technology is leading also to some disadvantages, mainly related to the increased complexity in the monitoring design.

When facing with the design of a monitoring system and, therefore, to the choice of suitable equipment the following two phases have to be considered:

- system implementation (including installation and start-up);
- monitoring system management and data dissemination.

System implementation is the phase where the previously design monitoring system is implemented, i.e the transition phase between "theoretical desk" implementation and "practical field application". It is obvious that as good and detailed the design has been done, as easy and rapid this phase will be. However, also in case of a "theoretically perfect" system design unexpected factors or lack of information can lead to problems.

The implementation of a system based on traditional contact instruments requires lower costs for equipment but higher costs for field operation and it is often affected by potential mechanical or electrical failures. Remote equipment are more expensive than traditional ones but they can be installed in safe and "confortable" places, thus reducing the installation costs and failure occurrence.

System Management is the following and operation phase where ordinary data collection is active and effective and the system efficacy must be maintained for the overall monitoring time. As good and detailed the design has been done, as easy and efficient the system maintenance, data collection, data processing and data dissemination will be.

Managing a system means to set-up a comprehensive number of procedures describing what has to be done and in which way, who is responsible for and who has to receive the results of the activity, who is in charge of data analysis and interpretation and decision making.
Maintenance means to ensure the system is performing as per design specifications. Special attention must be dedicated to the correct functioning of the instruments and their calibration using any possible site procedure in strict cooperation with those in charge of data analysis to dissipate doubts and uncertainties.

Traditional contact instruments require for a more expensive maintenance due to the need of human presence at the measuring points, presence of cables, communication devices and power sources, whilst remote equipment can be installed in more accessible and comfortable locations, reducing the time for operation, risks for operator and therefore, overall costs.

On the other hand, the management of remote sensing equipment require complex software for data processing, skilled people for data processing, validation and interpretation, subscription of contracts for data providing (in case of satellite images) etc., while standard equipment are simpler to be manage and used and independent from third parties.

From sentences above it is obvious that the criteria for the choice cannot be only the type of equipment or "technique" (remote or contact) since respective advantages and disadvantages can be more relevant depending on the case.

4.2 Main criteria

In what follows we will try to provide some suggestion about the main criteria to "make the right choice" in the design phase.

The starting points are:

- the "monitoring framework" which includes also the landslide features (paragraph 2)
- the "monitoring purpose" (paragraph 3).

A correct evaluation of the "monitoring framework" take advantage from the following data:

- bibliographic data;
- analysis of the available geological and geotechnical information (deriving from site investigations, laboratory tests etc);
- analysis of meteorological and environmental conditions (temperature, humidity, fog, rain, snow, visibility of the areas, distance of positioning or remote devices, etc..);
- analysis of site specific features (accessibility, visibility, drilling boreholes, power supply, cable paths, protections, presence of vegetation etc).

The comprehension of the "monitoring purpose" can derive only from a strong information flow with the customers and form the sensibility of monitoring designers with respects to customer needs. The following are the main information that can be gained:

- main parameters to be measured;
- expectation in terms of management, data dissemination, predictions, temporal frequency etc.;
- budget available.

Once the above mentioned steps have been concluded the following monitoring requirements will be evaluated, thus leading to the correct choice of equipment to be used:

1) Information depth;
2) Information density;
3) Monitoring Time;
4) Data sampling rate;
5) Range of variation;
6) Precision;
7) Costs.

1) Information depth refers the depth of information required. In some cases information about the "surface" displacement/deformation is enough, but more often if it is requested to measure below the ground level. Surface measurements can be made quite easily and accurately by means of "remote" measuring techniques. Instead, remote techniques are not able to penetrate the soil to measure, for example, movement within a sliding mass or the level or water. Hence, if information below the ground level is required "standard" contact instruments such as inclinometers, piezometers, total pressure cells are the only solution.

2) Information density refers to the number of monitored "points" from the spatial distribution point of view. Traditional contact techniques provide measurement only when the sensors is installed, while some remote techniques provide the simultaneous measurement of a large number of points or a "continuous" surface, with thousand of pixels (points) with a centimetres to meters resolution. This feature, for example, allows to overcome the problem of the selection and the reliability of the measuring points which is one of the most critical and dangerous aspects when using traditional surface or embedded instruments.

3) Monitoring Time means the time of monitoring, i.e. the duration and the date of the measurement required. Both contact and remote techniques require the installation of a sensor for the initiation of the measurement and they have no limitation in terms of "temporal duration". The only exception is Satellite InSAR (Bozzano and Rocca, 2012) which allow the perform historic monitoring thanks to the availability of images collected by Space Agencies since 1992.

4) Data sampling rate means the temporal resolution in data collection. The most common contact and remote sensing techniques allow for the automatic data collection and ma achieve temporal resolution ranging from seconds to tenths of minutes. Also in this case the only exception is satellite InSAR whose data sampling rate range form several days to some months.

5) The range of variation of the parameters means the maximum range of variation that can be measured. It is of great relevance to assess the measuring ranges to identify the capability to "follow" the full variation path of the parameters in case of strong deformation. Traditional contact techniques (e.g. inclinometers, extensometers) are often characterized by some limitations due to the mechanical resistance of used sensors (i.e. an inclinometer probe deformed more than some tenths of cm in a localized shear zone will fail). Remote techniques, on the other hand, do not have mechanical problems (since they are located far from the deforming area), but they can be affected by some trouble due to their operation principle (e.g. automatic recognition of target by Total Stations, phase ambiguity for InSAR).

6) Precision is the repeatability of measurements that is very important in the cases where small deformation (few mm/cm) must be detected. Theoretically, some remote techniques have a great precision (also 1/10 or 1/100 of mm), i.e. more than contact techniques. However, it is worth to note that the precision of remote sensing techniques is strongly influenced from atmospheric variation that can lead to reduction up to 100 times or more of the "nominal" precision of the equipment (i.e. precision achievable in controlled laboratory conditions). Also contact techniques are affected from the mechanical point of view by atmospheric conditions, however, their influence is lower than for remote ones.

7) Costs. Sensors and software for the processing of contact techniques are ordinary less expensive than remote techniques, however, contact instruments are often affected by high installation costs. For examples, embedded ones, require borehole which are expensive and require for access paths or aerial transportation of drilling equipment. Moreover, they require for power and data transmission devices (cable or radio link) which are, again, expensive and one of the weak rings of the measuring chain. On the other hand remote equipment do not require expensive "installation" procedure and, quite often one single instrument can be used for a whole landslide achieving anyway a great spatial coverage. Costs are also strongly dependent on the expected duration of the monitoring which.

5 Discussions and Conclusions

In landslide monitoring the choice of the monitoring system is often driven by "the equipment". Several reasons can lead to the choice of the "equipment" such as, i) *I trust in this equipment because already tested*; ii) *it is the less expensive*; iii) my equipment provider suggested me; iv) *it is the most precise*; v) I heard this equipment is (in general) very effective; vi) a sort of trend in the use of a specific one etc.

All these "reasons" however, are not technical reasons and are focused on the "equipment", which is only the arms and not the brain.

On the basis of our experience we argue that before make decision about a landslide monitoring systems a dedicated design is required as for all other engineering matters and this design must be driven by specific criteria.

A comprehensive knowledge of the landslide, including its physical and mechanical features, and the identification of the reasons for its monitoring (i.e. the monitoring purposes) are the main aspects to be considered. Without these preliminary evaluations no basis will be available for making any choice. It seems to be a quite obvious statement but it isn't since the design is not always a comprehensive phase of the monitoring activity.

Once the monitoring framework and the purposes are clear the choice of the monitoring techniques can be driven by several criteria such as: i) the information depth; ii) information density; iii) monitoring time; iv) data sampling rate; v) range of variation; vi) precision and also vii) the costs. Given the type and landslide and the monitoring purpose the most suitable mix between the above mentioned features can be identified and, therefore, the most suitable technique (and related equipment) can be identified among the available.

It has been showed that distinction between traditional contact monitoring and remote monitoring cannot be one the driving criteria; as a matter of fact, both categories are characterized by pro and cons that have to be considered and selected according to the specific application goals and resources. In general we have to be conscious that the choice lead to "the most suitable" solution and not "the best one" since the best doesn't exist!

Furthermore, it is noteworthy that very seldom the boundary and environmental conditions are so clear and defined and very seldom there are no unexpected situations or contingencies. The design of a monitoring system cannot be considered as a static procedure without any further adjustment. Therefore, the suggestion coming from the Knowledge Cycle – that means a continuous iteration of the design – operation – check – management process - must be considered. Field feedback must be considered and taken into account since it is impossible to forecast what it will happen at site, especially for complex landslides. Hence, we cannot neglect that the direct contact of the experts with the site situation is one of the most powerful "instrument" to understand the behaviour of a landslide.

Furthermore, the set up and start up of a monitoring system cannot be seen as the final step. As a matter of fact, monitoring is useless if data are not used appropriately. This implies the analysis of the collected and validated data that has to be performed by experts who know the context, the scope, the design criteria and the geotechnical and geological conditions as well as the alert / alarm criteria to set, if any.

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