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Toward Transportation Asset Management: what is the role of geotechnical monitoring?

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Response to Reviewers:	

Toward Transportation Asset Management: what is the role of geotechnical monitoring?

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Abstract
Geotechnical assets are vital for the efficiency of transportation corridors. Geotechnical monitoring can be a powerful tool for an effective maintenance of transportation assets and for safety purposes. Thanks to the technological evolution that has occurred during recent years, several monitoring technologies are now available to perform geotechnical monitoring. Ranging from remote satellite systems to contact instrumentation, it is now possible to perform a multi-scale approach in space and time, thus effectively supporting management and decision making actions. In this paper, three main categories of geotechnical monitoring are considered on the basis of the "monitoring purpose": knowledge monitoring, control monitoring and emergency monitoring. STN (Space-Time-Need) diagrams are proposed as a simple and useful graphic tool for the design of an effective monitoring plan that accounts for both the technical capabilities of the available monitoring technologies and the specific monitoring needs. Effective monitoring programs, suitable tools for data collection, management and processing combined with efficient models to support decision making leads to "Smart Geotechnical Asset Management" (SGAM). SGAM is a program that takes advantage of sensors collecting data in order to make risk assessment continuously updated over time.

Keywords: Geotechnical Assets, Observational Method, Geotechnical Monitoring, Remote Sensing, Transportation Corridors, Landslides

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1. Introduction

During recent decades the importance of communication and, therefore, lifelines have become crucial for mankind. The movement of people, raw materials and different types of products need transportation routes, and the sizes of these routes are constantly increasing. Each type of transportation route is built on "geotechnical assets". However, the impact of these assets is strongly dependant on the type of transportation (for example ground-based transportation is more sensitive to geotechnical assets than aerial based or water based transportation). The most common geotechnical assets along transportation routes are the following: i) embankments; ii) slopes/cliffs (both cut and natural); iii) tunnels; iv) foundations; v) earth retaining structures; vi) drainage systems; vii) levees; viii) reclaimed land and ix) coastal revetments (US DOT, 2013; Anderson et al, 2016; Mazzanti et al, 2016).

Despite the key role of geotechnical assets on the efficiency of ground-based transportation, systematic management is still not universally applied and regulated. Maintenance and management of means of transport, road signs, roads lights etc., are commonly considered as key factors for an efficient and safe transportation system. However, the maintenance and management of slopes and cliffs, embankments, earth retaining structures etc. currently have no standard regulations.

The dramatic impact of failures of geotechnical assets along transportation corridors have been widely demonstrated, both from the safety point of view and from the economic point of view. Considering both tangible and not tangible assets, a single landslide along a national road in a developed country may cause losses ranging from few million up to few hundred million US dollars. For example, in 2009, rockslides on I-40 in North Carolina and US-64 in Tennessee resulted in nearly six months of road closures with a total estimated transportation loss on the order of 200 million US$ (US DOT, 2013). Furthermore, it has been demonstrated that, in several cases, the cost of risk mitigation is significantly lower than the economic impact of a failure; Perry et al. (2003a-b) estimated that the mean cost for failures can be four to five times higher than the cost for mitigation and prevention.

Moreover, if appropriate maintenance is not performed, the risk of failure for geotechnical assets increases significantly over time. It is worth noticing that many of the transportation assets of developed countries are reaching (or have already reached) their originally planned life cycle.

For the above reasons, some countries are starting to consider geotechnical assets within the framework of their Transportation Asset Management (TAM) programs, thus leading to the development of Geotechnical Asset Management (GAM) plans. Based on Thompson (2016), a GAM Plan "is a written document, or a set of written documents and databases, which describes the processes and outputs of agency GAM activities". The GAM Plan complements other agency planning documents such as strategic plans, service plans, and investment plans, but it focuses on the preservation and performance of the agency's valuable infrastructure over a typical time frame of ten years.

For example, the New Zealand Asset Management Support [NAMS], published in 2006 on the International Infrastructure Management Manual, declared that "the purpose of transportation asset management is to meet a required level of service, in the most cost-effective manner, through the management of assets for present and future customers" (NAMS, 2006). Today, several other countries, including USA and UK, are developing GAM programs for effective management of their complex road and railway transportation networks (Power et al, 2016). In 2007 the UK established the Geotechnical Asset Owners Forum (GAOF) as a platform for those involved in the management of geotechnical and related assets. The aim is to share and exchange ideas, information and research themes (http://www.ciria.org/gaof/).

Despite the above positive activities, several efforts are still required for the effective development of a geotechnical assets management (GAM) program, due to some complexities. In some cases, we are dealing with "natural objects" (e.g. slopes, cliffs), the knowledge of which is intrinsically lower than that available for man-made structures. These assets are also characterized by a high spatial variability, thus making the risk assessment difficult, costly and not completely reliable. For example, in the case of large landslides it is very difficult to define the size of the corridor to be assessed along the route. The most relevant economic and safety issues for geotechnical assets are "extreme events" (e.g. failures) that are characterized by low temporal frequency and high magnitude. Hence it is very hard to assess the temporal predictability of geotechnical failures, especially on a transportation network scale.

Geotechnical monitoring can play a key role in geotechnical asset management. After a brief historical review of geotechnical monitoring, an overview of different available technical solutions will be presented. This will be followed by a discussion of the different achievements that a suitable monitoring plan can provide to geotechnical asset management.

2. Brief history of the observational method in geotechnical engineering

The observational method (OM), also known as the "learn-as-you-go" method, was proposed by Karl Terzaghi and Ralph Peck, two of the fathers of the modern geotechnical engineering (Terzaghi, 1937; Peck, 1969). The practical experience in challenging engineering projects, led Terzaghi and Peck to the awareness that "uncertainty" is common in geotechnical engineering. They were conscious that, despite a suitable investigation, calculation and computation, each geotechnical project can be characterized by "unpredicted" events, and "unforeseen" findings.

Therefore, accepting that over-conservative designs are not economically acceptable, they suggested the "observational method" as a tool to achieve designs with reasonably low factor of safety, without neglecting safety during construction. By using the observational method, the project can be continuously upgraded and improved during the construction phase based on the "observation" and "learning" procedure. Several examples of the benefits of OM are described by Peck in Dunnicliff & Deere (1991). In later years the importance of the observational method has also been demonstrated in the design phase, thus leading to the development of the Observational Method Design as an alternative to the Traditional Design (Nicholson et al, 1999) by stating that "The Observational Method in ground engineering is a continuous, managed, integrated, process of design, construction control, monitoring and review that enables previously defined modifications to be incorporated during or after construction as appropriate". Kovari & Lunardi (2000) showed an interesting example of application of the OM during the construction of a tunnel in Italy, thus leading to the development of a new method in the construction of tunnels named ADECO-RS (Analysis of Controlled Deformations in Rocks and Soils) (Lunardi, 2008). Continuous geotechnical monitoring during tunnelling excavation is the basis of the ADECO-RS excavation method.

The growth of the OM has been associated with the development of affordable geotechnical monitoring equipment (such as piezometers, strain gauges and settlement measuring systems). However, only in the 1970s – 1980s measurements with geotechnical field instrumentation become a recognized discipline, thanks also to some milestones: i) standards delivered by international associations (ISRM, 1981a-c), ii) publication of the first books (Hanna 1985; Dunnicliff, 1988 and 1993) and iii) the first series of international conferences (FMGM, 1983). Rapid developments of geotechnical monitoring occurred in the late 1990s while, at the beginning of the 21st century, a new paradigm in geotechnical monitoring was opened by "remote sensing" (Mazzanti, 2012). In recent years, conferences and courses dedicated to geotechnical monitoring and instrumentation have been developed, such as the annual International Course on Geotechnical and Structural Monitoring (www.geotechnicalmonitoring.com) held in Italy and the GE Instrumentation and Monitoring in UK.

Table 1, assembled by the author based on technical papers, personal communications with manufacturing companies, and analyses of patents, shows some key milestones in geotechnical monitoring from 1950 to today.

1950s	1960s	1970s	1980s	1990s	2000s	2010s
Stressmeter						
Levelling			Continuous Monitoring			
Theodolite			US standards	Early Warning Monitoring	European Standards	Digital Image Correlation
Extensometer	Vibration Monitoring		Total Station	GSM data transmission	Laser Scanner	Drones
Piezometer	Submarine Monitoring	Data-logger	Time Domain Reflectometry	Fibre Optics technology	Multi-parametric borehole systems	Web based data management
Load cell	Inclinometer	Laser distance-meter	In place inclinometers	GNSS Technology	Interferometric Radar technology	Wireless monitoring

Table 1: Some milestones of geotechnical monitoring from 1950 until today.

Table 1 shows that some commonly used technologies such as piezometers, extensometers, load cells and levelling have been used for more than 60 years, while other common monitoring technologies such as in place inclinometers, total stations and GNSS have been developed more recently (e.g. GNSS less than 25 years ago). Data-loggers, that allow for continuous and automatic data acquisition, were developed in the 1970s, while the first protocols for remote control and data communication were available since 1990s. We can conclude that real-time monitoring is a very recent practice. Furthermore, Radar and Laser Scanner monitoring technologies have been effectively deployed only in the last 15 years. Today, several technical solutions are available for monitoring different geotechnical/geo-mechanical parameters. In recent decades a strong increase in software for data management, data processing and data visualization has been made available to practitioners, thus allowing them to make use of the increasing amount of monitoring data.

Successful examples of the importance of geotechnical monitoring in supporting challenging engineering projects are now available, thus demonstrating the importance of the observational method in geotechnical engineering practice (e.g. Di Biagio & Høeg, 1989; Dunnicliff & Deere, 1991).

As examples, piezometers, pendulums and levelling supported the project of stabilisation of the leaning Tower of Pisa (Burland et al, 2009). Extensive surface and subsoil geotechnical monitoring systems are used at the Zelazny Most tailings dam in Poland to support the development of the dam (Jamiolkowski, 2014). Geotechnical monitoring has become standard in most tunnelling projects around the world (Kavvadas, 2005) and guidelines have been developed for this purpose (BSI, 2011, ASG, 2014). Geotechnical monitoring is also effectively used in the management of large landslides by the development of early warning systems, where automatic monitoring systems are used. In some cases, a continuous monitoring system is considered an alternative to extremely expensive stabilisation works, such as at the Ancona landslide in Italy (Cardellini & Usinami, 2008) and the Aknes landslide in Norway (Blikra, 2008). An interesting review of some landslide early warning systems, including a description of the monitoring networks, can be found in Michoud et al. (2013).

Challenging engineering projects related to transportation have given a strong impulse to the development of the observational method and to the increase and improvement of equipment for field measurements (Bozzano et al., 2011; Brunetti & Mazzanti, 2015). Transportation assets can now receive strong benefits from these developments in the practice of managing geotechnical assets.

The presence of a dedicated section in Eurocode 7 is further confirmation of the role assumed by the observational method in modern geotechnical engineering (BSI, 2004).

It is worth emphasizing that monitoring of geotechnical parameters is characterized by uncertainties. The availability of several technical solutions, each one characterized by specific advantages and limitations, is making the job of "geotechnical monitoring professionals" much more complex than in the past, thus needing strong specialization and design capabilities. In 1970 Ralph Peck declared "We need to carry out a vast amount of observational work, but what we do should be done for a purpose and done well." This is just as relevant today as it was in 1970.

3. The "how" of Geotechnical Monitoring

Nowadays, geotechnical monitoring is done by mechanical or electronic equipment that measure the temporal changes of soil/rock parameters useful to understand, and eventually predict, the ground behaviour.

3.1 Geotechnical parameters

Geotechnical assets, especially natural ones such as slopes, are characterized by a strong variability and heterogeneity, and the identification of the relevant parameters to be monitored is challenging. The following key geotechnical parameters have been identified for an effective and useful monitoring plan (Dunnicliff, 1993; Dunnicliff et al, 2012):

- **Displacement** (also referred to as deformation) is one of the most common parameters used in geotechnical monitoring, and it can be measured by several sensors and at different levels (in the surface and underground). Displacement can be directly measured by distance transducers or derived by the measurement of the inclination through suitable sensors.
- **Vibration** and **acoustic emission** are becoming important parameters, used for the dynamic characterization of soil/rocks, especially, during the civil works.
- **Pore water pressure** monitoring is the measurement of the pressure of water in the pores in the soil. **Joint water pressure** monitoring is similar, for rocks. These are key parameters that control the behaviour of geotechnical materials.
- **Stress** is measured in soil and rock through the installation of sensors or during the construction or during the excavation.
- **Load** and **Strain** are other common parameters used in monitoring structures.
- **Temperature**, is a useful parameter in geotechnical monitoring as it can provide insights on: a) the presence of external factors that influence the soil/rock temperature (e.g. presence of water); b) the displacement/stress that can be induced by temperature variation.

In most cases, the measurement of a single parameter is not enough for a comprehensive understanding of the behaviour of a geotechnical structure.

3.2 Geotechnical monitoring instruments

Geotechnical instruments can be classified in two main categories, i.e. “contact” and “remote”. Contact systems need the physical contact between the instruments and the ground while remote instruments do not require such contact, as they are mainly based on sensors receiving, and often emitting, electromagnetic waves.

Contact methods are today the most common in monitoring practice because of their longer history (Table 1) and the capability to measure all the key geotechnical parameters described in section.3.1.

The development of remote methods is much more recent (see Table 1), and therefore their application is not always considered as a standard for geotechnical monitoring. However, especially in the last few years, the use of remote methods is increasing drastically. It is worth noting that, in contrast to contact methods, remote ones are able to measure only displacement, vibration and surface temperature.

In Table 2 the most common contact and remote geotechnical monitoring instruments are classified in relation to the specific geotechnical parameters that they can measure. Most comprehensive reviews of these instruments can be found in Dunnicliff (1993; 2012) and Mazzanti (2012) for contact and remote, respectively.

Parameters	**Contact instruments**	**Remote instruments**
Displacement (deformation)	Surface and probe Tiltmeter, Inclinometer, Extensometer, Liquid Level Gauge, Crack Gauge, TDR, Fibre Optic, Pendulum, Deflectometer, Convergence Gauge	GNSS, Total Station, Optical Levelling, Lidar, Satellite SAR Interferometry, Terrestrial Interferometric Radar, Digital Image Correlation, Photogrammetry
Vibration	Accelerometer, Velocimeter, Seismometer, Geophone	Terrestrial Interferometric Radar, Digital Image Correlation
Acoustic emission		
Groundwater pressure	Piezometer, Observation Well	n.a.
Stress	Earth Pressure Cell, Stress-meter	n.a.
Load & Strain	Load Cell, Strain Gauge	n.a.
Temperature	Thermometer, Thermocouple	InfraRed Camera

Table 2: List of the main geotechnical contact and remote equipment used for the monitoring of the key geotechnical parameters.

The evolutionary trend of geotechnical sensors has been very rapid in recent years, thus leading, to the development of multi-parametric apparatus (able to measure simultaneously different parameters) such as the DMS multi-parametric borehole monitoring system (Lovisolo et al, 2003). Also systems able to monitor the displacements in a borehole at different depths simultaneously, such as the shape-accel-array (SAA) system (Bennet et al, 2009). Fibre optics distributed instruments are today able to check simultaneously temperature and strain changes along several km (Zeni at al, 2015).

It is also worth noticing that Micro-Electro-Mechanical-Systems (MEMS) sensors are leading to a significant reduction in the size of instruments, and to an increase of endurance with a reduction in cost (Sellers & Taylor, 2008).

Remote sensing technologies are more revolutionary in geotechnical monitoring practice, for example the Terrestrial Laser Scanning apparatus are able to collect millions of points in few minutes (Abellan et al, 2009), while Terrestrial Synthetic Aperture Radar are able to measure simultaneously the displacement of thousands of points with a mm accuracy at a distance of some km (Montserrat et al, 2014). Satellite InSAR technologies are providing the opportunity to monitor displacement occurred in the past with mm accuracy (Kempes, 2006).

Multi-temporal near surface geophysics deserves a special mention as a geotechnical monitoring tool. It is a well-known and commonly used spectrum of techniques for subsurface geological and geotechnical investigations that, in the last few years, has been applied by some authors for monitoring purposes. Specifically, time-lapse Electrical Resistivity Tomography (ERT), surface seismic waves and electromagnetic induction by multi-temporal surveys have been used to monitor the changes of geotechnical features such as soil moisture and ground water (Chambers et al, 2014; Gunn et al, 2015; Bergamo et al, 2016).

In general terms, the performance of each geotechnical monitoring instrument can be analysed by the following key features: i) precision or accuracy; ii) temporal resolution; iii) reliability & temporal stability; iv) information density; v) geometry; vi) degree of interaction with the monitored object; vii) size of the instrument; viii) durability. Some additional features characterize remote monitoring systems such as: ix) the spatial resolution; x) sensing distance; xi) size of the monitored area. Some leading features are more extensively discussed below.

3.3 The "time-factor" of geotechnical monitoring instruments

"Time" is a typical feature for each parameter and instrument. The multi-temporal measurement of a parameter makes the difference between "measure" and "monitoring". In dealing with the time factor we must account not only with the instrument or monitoring operator capabilities but also with the geotechnical structure that need to be monitored.

When talking about the length of a monitoring activity, we often hear the words "long term" or "short term"; however, "long" and "short" are qualitative words as their physical meaning is closely connected to the monitored objects and the monitoring "purposes" (see section 4). Long term can be days, months, years and also decades. When long means years or decades, some features of the instruments become relevant such as the durability and the temporal stability (Anderegg et al, 2014).

However, apart from the overall length of the monitoring, there is another important "time" related feature to be considered: the temporal frequency of data collection (also referred as temporal resolution). Words such as "periodic monitoring" or "continuous monitoring" are commonly used but they are also qualitative words. Strictly speaking, "geotechnical monitoring" is always "discontinuous", in that the measurements are collected in a "discontinuous" mode (even if sometimes we can collect several data points per second). Looking at the mechanical behaviour of a process, each temporal frequency that allows us to follow the complete evolution of a process can be defined "continuous". In other words, the "continuity" of a monitoring activity depends on the relationship between the unit base of the process evolution pattern (T_E) and the temporal frequency of data collection (T_C). Each monitoring program that follows the following equation can be considered continuous:

$$T_C > \text{Unit base of } T_E$$

The most recent paradigm of geotechnical monitoring is the "past monitoring", made possible by the availability of globally distributed data collected in the past by third parties. The main example is the Satellite SAR Interferometry technology (Hanssen, 2001; Kampes, 2006) that, thanks to the availability of images collected from the year 1992 by different satellite missions, today allows the "monitoring" of processes that occurred in the past, before the beginning of the monitoring program. In other words, it can be considered a sort of "displacement time machine" with a view over the entire world.

3.3 The "space-factor" of geotechnical monitoring instruments

The "space factor" is another key feature in geotechnical monitoring. An extreme variability exists in terms of "spatial scale", i.e. the extension and localisation of the monitored area/object. Some sensors are characterized by precise localization and measure small piece of the ground, thus providing local information that must be extrapolated on the whole structure. Other sensors are characterized by coarse localization precision but the capability to simultaneously measure very large areas.

In general terms, "contact methods" are characterized by higher localization precision but reduced spatial information density and limited size of the monitored area, while, "remote methods" are characterized by lower localization precision but higher information density and higher size of the monitored area. To give some examples, a unidirectional crack-meter is a local sensor measuring a single crack (it is intrinsically representative of what is occurring in a "cm wide area") whose localization is very precise. On the other hand, a ground based SAR instrument is able to measure simultaneously the displacement of thousands of points distributed over few square km, but the size and localization of the measured points is on the square meter order. Similarly, distributed fibre optics (Glisic & Inaudi, 2008) can provide information distributed along a linear section several km long, but the localization precision of each measure in of metric order.

Four main categories of monitoring systems can be defined in terms of "space-factor": a) point based monitoring; b) linear based monitoring; c) spatial based monitoring; d) volumetric based monitoring (Figure 1).

It is worth noticing that most of the contact systems are in group a) and most of the remote systems are in group c). New systems such as distributed fibre optics or SAA are in group b), while only the integration of the above may allow for a volumetric control, i.e. group d).

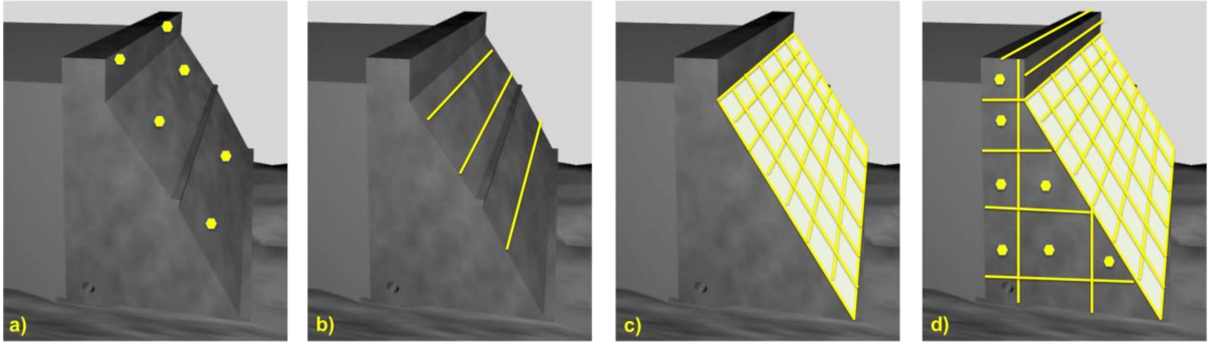

Fig. 1: schematic description of the 4 main categories of space monitoring: a) point based; b) linear based; c) spatial based; d) volumetric based.

3.4 Space-Time-Need

Space and time features described above can be summarized in a synoptic STN (Space-Time-Need) diagram, showing the space and time performance of different monitoring technologies. Such a diagram identifies the regions where each monitoring system can be effectively performed, thus providing an easy-to-use tool for a preliminary monitoring design. Figure 2a and Figure 2b show two examples of STN diagrams for contact and remote methods respectively. In the diagrams we can easily identify the monitoring solutions that may be used for a widespread analysis (e.g. satellite SAR Interferometry and Distributed Fibre Optics), and those more appropriate for localized monitoring (e.g. inclinometers, extensometers etc).

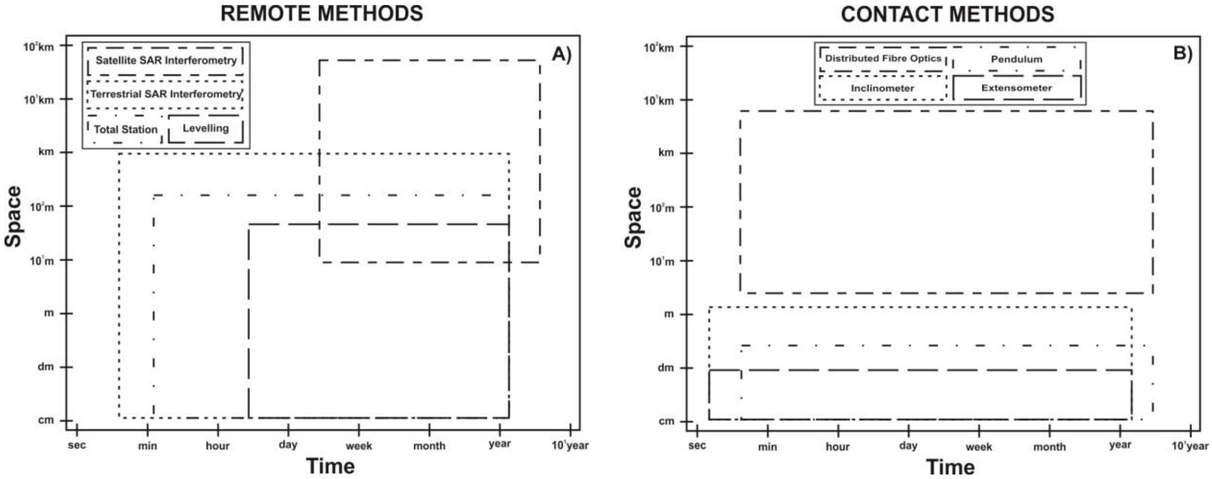

Fig.2: STN (Space-Time-Need) diagram showing the position of different Remote (A) and Contact (B) geotechnical monitoring methods. X axis refers to the data sampling rate; Y axis refers to the spatial coverage. Labels are related with boxes having similar line style.

3.5 Geotechnical Monitoring Networks

The recent trend of geotechnical monitoring is toward monitoring networks: the combined use of multiple sensors by integrating contact and remote methods, taking the advantages of each one and reducing the respective limitations. Monitoring networks made of different sensors allow the collection of multi-parametric information and the reduction of uncertainties by the cross-check of data. Especially for ageing geotechnical assets aimed at increasing the life cycle, we are moving toward systems able to monitor continuously large areas. In the last few years, we are observing a strong reduction of the sensor's power absorption and the increase of efficiency of the batteries (Ahmed et al, 2016).

Continuously operating monitoring networks are leading to the collection of huge amounts of data that must be transmitted almost in real time to the data operation centres, to be used for diagnostic purposes. In this perspective, wireless systems are taking a relevant position in the market, thus substituting wire systems (Ramesh, 2014; Fernandez-Steeger et al, 2015; Maddison & Smith, 2014; Benoit et al, 2015; Spencer et al, 2016).

Another need for an efficient management of massive amount of data is the visualization and operability by the end users. Web-based data management systems are becoming a standard (Cook, 2010), especially for the largest engineering projects (Thorarinsson, 2007; Rackwitz et al, 2013).

3.6 Geotechnical data driven models supporting decisions

The trend toward continuous and multi-parametric monitoring is opening new perspectives for the effective management of geotechnical assets. However, effective decisions must be supported by tools that are able to translate data into information in an automatic or semi-automatic way. Different solutions have been developed in recent years for both spatial widespread periodic checking, such as Advanced Satellite InSAR for the early identification of geohazards along transportation assets (Bruckno et al., 2013; Bouali et al., 2016), and for the real time evaluation of risk and alerting. If a periodic check of geotechnical assets can be an effective support for the maintenance of large transportation networks, the most challenging objective for safety purposes is the development of automatic or semi-automatic procedures for the early detection and alerting. In recent years several early warning systems able to manage in real time the risks due to slope failures along transportation assets have been proposed. The challenge of these approaches is to forecast the slope evolution, thus providing alert levels suitable for managing infrastructures and reduce the “response” time for interventions. Based on Bozzano et al. (2017), three main approaches can be used for the landslide forecasting: a) an observation-based approach (OBA), b) a semi-empirical approach (SEA) and c) a statistical-based one (SA).

OBA is focused on searching objective co-relations among predisposing and triggering factors and induced effects. This approach is based on detailed engineering-geological data and evolutionary models (Thiebes et al, 2014).

SEA is based on simplified rheological models and time-by-time calibration based on long term displacement time series (Voight, 1989; Federico et al, 2012). This approach does not require detailed information about the slope, but only good monitoring data. It may allow for the temporal prediction of slope failures, but it fails for slope processes characterized by time-variant loading/controlling factors (Bozzano et al, 2014; Mazzanti et al, 2015).

SA adopts statistically based cross co-relations among different parameters to identify trend anomalies of continuously recorded data. This approach is based on the semi-automatic data-flow-to-data-processing analyses of huge amount of data, to be managed in very short time and accounting for early warning strategies (Bigarré et al, 2013).

The recent development of cloud-systems for dataset storage and the increasing capabilities of data processors are making the application of the above described approaches easier and effective also for tunnelling and pipelines projects (Ding & Zhou, 2013; Zhang et al, 2015). In some cases, geotechnical assets monitoring can be part of an overall risk management programs implementing BIM related technologies as showed by Zou et al. (2016).

4. Monitoring Geotechnical Assets: a multi-purpose tool

A key factor of success for a geotechnical monitoring program is the careful consideration of its “purpose”. Specifically, the following questions must be answered each time that a monitoring program is designed: i) why do we need to monitor?; ii) what do we measure?.

In terms of “why monitoring”, three main monitoring categories can be considered: i) knowledge monitoring; ii) control monitoring; iii) emergency monitoring.

Knowledge monitoring, in the author's opinion, is one the most important for transportation geotechnical assets management purposes, even if it is one of the least used today. The aim of this type of monitoring is to quantitatively test and assess the performance of geotechnical assets in ordinary operational conditions. Knowledge monitoring should be considered an investigation geotechnical tool at the same level of other geotechnical field tests, but with the advantage of the "time-factor" (i.e. variation in time). This kind of monitoring may allow to identify and localize unknown areas affected by potential failures, thus giving support to the prioritization of interventions. This type of monitoring is made complex by the need to investigate widespread areas. However, some "remote methods" (such as Radar and Laser technologies) promise to provide a key contribution to this kind of monitoring in the near future.

The most common applications are: i) choice of the suitable routes and analysis of geological/geotechnical risks along a route in the design phase of engineering projects; ii) long term maintenance procedures aimed at the early detection of potentially unstable segments and potential risks or deteriorations; iii) widespread screening of the assets conditions after paroxysmal events like earthquakes, floods etc.

Control monitoring is probably one of the most used in the management of transportation geotechnical assets. The aim of this type of monitoring is to quantitatively check the evolution of well-known problems that affect geotechnical assets, in order to help define service levels and the management of risk associated with failures. Control monitoring can take advantage of each kind of monitoring sensor and can be continuous or discontinuous in time depending on the type of problem to be dealt with.

The most common applications are: i) monitoring of transportation routes (e.g. embankments, tunnels, etc.) and potential interference (e.g. existing surrounding buildings and infrastructures) during the construction phase; ii) maintenance procedures for the control of critical segments (e.g. segment crossing active landslides); iii) verification of the condition of high risk areas.

The use of **emergency monitoring** is increasing, thanks to the capabilities of new monitoring equipment in terms of frequency in data collection, processing and transmission. The aim of the emergency monitoring is to continuously control transportation routes and provide an alert (often automatic) in case the risk become unacceptable. Landslides are one of the most common cases where emergency monitoring is used in order to close a transportation route if a failure has occurred, or if it is expected to occur soon. Emergency monitoring plans (also known as early warning systems) need continuous data acquisition and, possibly transmission with a high temporal sampling rate. The reliability of the monitoring system is mandatory and monitoring networks are preferred in order to guarantee the continuous operation and avoid false alarms. Emergency monitoring can be used also as a short term supporting tool for increasing the safety of workers during dangerous operations. In this perspective, ground based Radar and Laser systems are very effective.

The most common applications are: i) continuous monitoring of critical areas along transportation routes and potential interference (e.g. existing surrounding buildings and infrastructures) during the construction phase for safety of structures and workers; ii) continuous early warning systems for the early detection of risks during standard operating conditions.

Figure 3 shows the three types of monitoring in the STN diagram, while Table 3 shows in a synoptic and schematic view the main applications and most commonly used instruments for the three types of monitoring purposes. This table must be considered a schematic and approximate one,based on the most common standards applied in recent years of geotechnical monitoring practice.

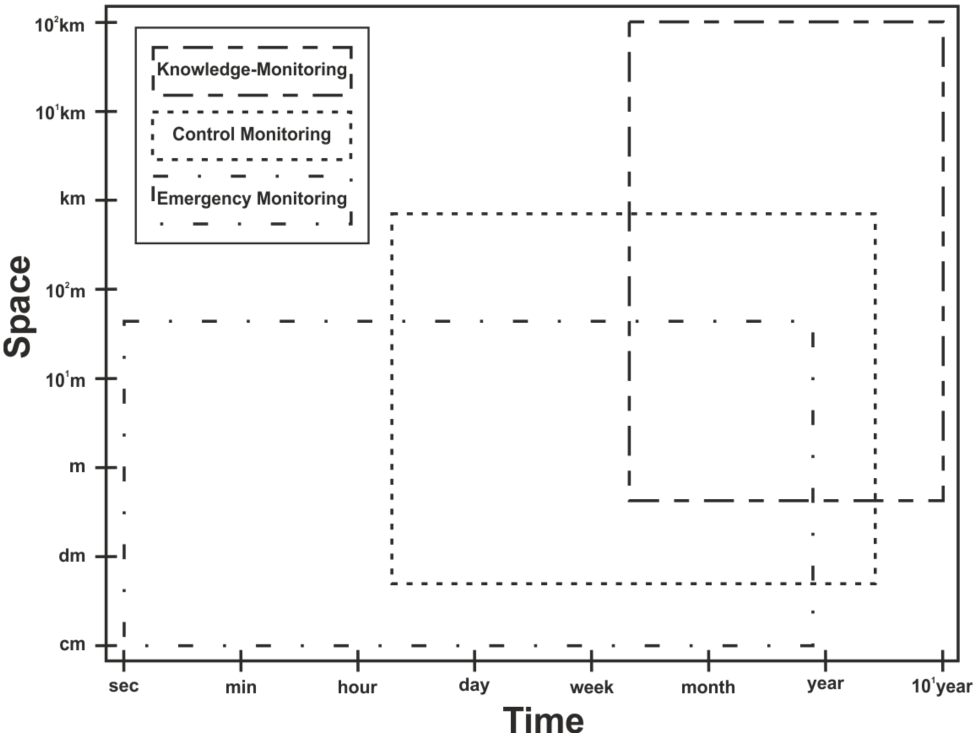

Fig.3: STN (Space-Time-Need) diagram showing the position of the different types of geotechnical monitoring described in Par.4. Labels are related with boxes having similar line style.

	Common applications	**Common Instruments**
Knowledge Monitoring	Design phase Standard maintenance Screening after paroxysmal events (earthquakes, floods, etc)	LiDAR, Satellite SAR Interferometry, Terrestrial Interferometric Radar, GNSS, Photogrammetry, Observation Well, Piezometer, Inclinometer, TDR, Earth Pressure Cell, Accelerometer, Velocimeter, Seismometer
Control Monitoring	Construction phase in medium risk areas Advanced maintenance (critical segments) Verification of high risk area	LiDAR, Satellite SAR Interferometry, Terrestrial Interferometric Radar, GNSS, Photogrammetry, Total Station, Optical Levelling, Digital Image Correlation, Observation Well, Piezometer, Inclinometer, TDR, Extensometer, Earth Pressure Cell, Stress-meter, Load Cell, Strain Gauge, Fibre Optic, Pendulum, Deflectometer, Convergence Gauge, Surface and probe Tiltmeter, Liquid Level Gauge, Crack Gauge, Accelerometer, Velocimeter, Seismometer
Emergency Monitoring	Construction phase in high risk areas Early warning systems for operation in high risk areas	LiDAR, Terrestrial Interferometric Radar, GNSS, Total Station, Piezometer, Inclinometer, Extensometer, Strain Gauge, Fibre Optic, Pendulum, Surface and probe Tiltmeter, Liquid Level Gauge, Crack Gauge, TDR, Convergence Gauge, Accelerometer, Velocimeter, Seismometer

Table 3: Synoptic table showing the typical applications for each type of monitoring and the most common geotechnical instruments used.

In some cases the three types of monitoring can be consequential one to the other in the frame of complex engineering project as described by Brunetti & Mazzanti (2015).

5. Conclusions and Outlooks

Geotechnical Assets Management (GAM) programs are expected to become a standard for transportation agencies, especially in developed countries that are faced with assets that have reached, or are approaching, the end of their estimated life cycle (Habel, 2013). However, the complexities of assessing geotechnical risks along transportation networks are slowing down the implementation of GAM programs.

Geotechnical monitoring can provide a continuous updating of geotechnical risk assessment along transportation routes especially if a multi-scale approach (both spatial and temporal) is applied. Today, a suitable integration of contact and remote monitoring technologies can provide a comprehensive answer at each scale. Monitoring networks (eventually making use of wireless data transmission systems) supported by web-based data dissemination and visualization tools are able to support final user at each scale with in a synoptic view.

Cost reduction of monitoring programs is likely to be reached in the next few years by the use of innovative sensors (e.g. MEMS, cables for fibre optics) or new satellite missions providing free of charge images (both optical and SAR) but, even more, by the increase of the geotechnical monitoring market. Recent trend market analyses, like the one by Future Market Inside called "Structural Health Monitoring Market: Global Industry Analysis and Opportunity Assessment, 2016–2026", have estimated a 10% per annum increase of the structural and geotechnical monitoring market in the next 10 years. Recent studies, are also focusing on the evaluation of cost benefit and sustainability of investment for long term monitoring programs, as this is considered a key step for a standardized use (Carrìon et al, 2017).

At the same time, data driven numerical and statistical models need to be developed and extensively tested in the next years for supporting decision makers. This is the final step towards "Smart Geotechnical Asset Management" programs, i.e. GAM programs that take advantage of data collected by monitoring sensors for an efficient management of transportation assets. A geotechnical monitoring plan may allow to:

- increase the efficiency of transportation corridors by avoiding interruptions due to geotechnical failures;
- increase the safety of users along transportation corridors;
- increase the safety of workers along transportation corridors;
- extent the life cycle of transportation structures by testing their residual safety factors and continuously controlling their evolution in time;
- reduce the cost of geotechnical asset management by promptly identifying the segments needing for more maintenance;
- reduce insurance costs for transportation assets owners;
- support transportation assets mangers in decision making, both for maintenance and remediation actions and for safety insurance.

In the future, early warning monitoring systems are expected to be also an alternative to "structural interventions" for risk mitigation along transportation corridors. Especially for large landslides crossing transportation roads, “passive” interventions can be the only reasonable actions to be performed, because of the extremely high costs of active “structural interventions”.

The main cultural revolution that is likely to happen in transportation assets management will be the systematic inclusion of permanent monitoring sensors in each geotechnical asset, starting from the design phase. Some experimentations already exist, like the installation of extensometers during the construction of tunnels for measuring convergences or the installation of fibre optics along critical lines. Innovative monitoring technologies like Distributed Fibre Optics, Satellite SAR Interferometry, UAV based optical monitoring are not far to be ready for a systematic and continuous control of transportation assets. A key role in this cultural and technological evolution is expected from geotechnical designers that should consider the “geotechnical monitorability” as a key design factor, thus opening the new era of the “observational method”.

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