ROLE OF GEOTECHNICAL MONITORING: STATE OF THE ART AND NEW PERSPECTIVES

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Summary:

As geotechnical engineers, we all well know that, each project involving rock or earth, underruns the risk of facing surprises. We also are well aware of the fact that each of our designs is, to some extent, hypothetical. These facts are coming from our privilege of working with materials created by nature and, therefore, different from any theoretical model that we choose to describe them. Consequently, the uncertainties involved in the behaviour of a geotechnical structure are generally larger than those related to any other engineered structure are. Field observations and in particular quantitative measurements of specific physical quantities are the only antidote to the described inherent limitations and allow the geotechnical engineer to efficiently and safely design a project, on one side, and the constructor to carry out the work economically and effectively, on the other. The paper introduces the main aspects of geotechnical monitoring, from design to implementation, and outlines the principles governing the choice between traditional or innovative instrumentation.

Key words:

Geotechnical monitoring, observational method, instrumentation, early warning, MEMS, field observation.

1. INTRODUCTION

Field instrumentation is vital to the practice of geotechnical [8] and geotechnical engineers must have sound knowledge of monitoring instrumentation since, for them, it is an essential working tool. The second half of the last century has seen a major implementation of geotechnical instruments; during the last 30 years, there has been an important turning towards electrical instruments some of them becoming increasingly complex and efficient. Although originally less reliable than optical and mechanical instrumentation, the electrical devices have gained many improvements and are now becoming the standard and most required instrumentation. This is due not only to the improvement of their reliability but also to the current requirements of automation in the collection and analysis of geotechnical data. Critical structures exposed to landslide risk, like dams, quarries, highways, etc., need early warning or near-real time monitoring systems, which have to provide an immediate warning when certain thresholds are reached. This allows the prompt activation of all the required emergency procedures.

2. PLANNING GEOTECHNICAL MONITORING

Notwithstanding the importance of instrumental monitoring in the geotechnical field, the mere installation of instruments, even of those of highest quality and reliability, cannot guarantee proper design and avoidance of problems during construction. Unappropriated instruments located in unfavourable positions may provide confusing results, if not misleading indications. It is therefore mandatory to design accurately the monitoring layout in order to achieve the best results at the appropriate costs. Failure to consider an upper limit in the number of installed instruments can cause confusion and create difficulties in accessing the data, while relying in few instruments in order to save money can end up in lack of relevant data and inability of providing the required answers. Because this is, in fact, the role of monitoring instrumentation: answering a specific question during the progression of construction or, in case of natural phenomena, indicate and follow the response of the geotechnical system to the variation of external conditions.

2.1. Type of monitoring

The first condition that the designer should consider is the typology of the geotechnical monitoring required. The choice of the physical entities to measure, the instrument typology and positions, the structure of data collection are very different depending on the monitoring objectives. In the following paragraphs, there are the most diffused monitoring cases with their relative considerations.

2.1.1. Monitoring of natural phenomena

The definition of natural phenomena monitoring refers to all the geotechnical monitoring which want to investigate the tensio-deformative behaviour of natural materials or natural materials used as construction materials (like for example reinforced ground, dams, etc.) whenever subjected to the modification of boundary conditions (water pressure, temperature variation, hydrometric levels of river and/or channels).

In the case of the monitoring of natural elements like landslides, the choice of the monitoring system should start from the hypothesis related to the lithological and stratigraphic characteristics of the area under examination and the typology of the expected instability phenomenon. For example, it is immediately clear that the monitoring of a sliding movement is very different from that of a rock fall. In the first case it is necessary to define the depth of the sliding surface in the area where the technician wants to place an inclinometer casing, while in the second case it is important to define the discontinuity families, which have to be investigated using extensometer techniques. For the purposes of the monitoring of surface movements, it is necessary to prior establish the expected displacement velocity: it is known that some technics of remote monitoring, like terrestrial radar, could have problems finding the position of permanent scatters, if these move at a speed too high than the frequency of the measurements. Other techniques like photogrammetry could be more functional in those conditions ([20]). The expected displacement velocity, related also to the magnitude of these displacements, is fundamental also in the choice of the most appropriate sensors for the detection of local displacements. If the expected displacements are of small size and protracted over time, it is necessary to use instruments, which have both a high accuracy and a good repeatability, in order to detect the real effects and do not confuse them with the instrumental noise. In addition, the goal of monitoring deserves some considerations: if the aim is to study and control the evolution of phenomenon, data acquisition could be manual and/or local, without the necessity of an immediate check of the measured output. Vice versa, if the finality is an alert or alarm, it is necessary to collect automated measures, which have to be processed and evaluated in a very short time (near real time) with the possibility to quickly contact the responsible of monitoring if a predefined threshold is exceeded. Regarding this particular monitoring field, the definition of thresholds should be the result of a preliminary modelling of the potential phenomenon, always subjected to uncertainty. The typology of the mathematical model used and the consequently theoretical hypotheses involved are related to these uncertainties. In particular, it is necessary to investigate the theoretical hypotheses regarding the geometry, the lithology and the intrinsic uncertainties associated with the definitions of the mechanical and hydrogeological characteristics of the natural materials. In these conditions, it would be appropriate to create an automatic data acquisition system with statistical self-learning algorithms [4] that, after a preliminary phase of training and collection of the measures, could identify significant anomalies in the raw data. This kind of approach is weak at the beginning of the monitoring process but can rapidly reach an acceptable accuracy level when the data sample becomes significant. Another advantage of this approach is related to the continuous automatic refinement of the critical parameters estimated. In landslide monitoring it is also fundamental the recording of pore pressures (even negative pore pressure), temperatures, rainfall, hydrographic levels adjacent to the monitored slope and, where it is feasible, the load variation of reinforcing elements (i.e. rods or nails). A key parameter is the electrical power. A solar panel and a backup battery supply energy where the direct connection to the electrical line is not possible. The control unit must read instrumentations at a sample rate, which has to be compatible with the risk related to the site but also to the power consumption. It follows that it should read the sensors with the correct frequency and, eventually, be able to increase or decrease it according to the monitored outcomes. If the rate is too high, the battery could run out of charge, especially during night time or storms, when the solar panel is ineffective; furthermore, a large amount of data to be interpreted are generated causing long computing time and, sometimes, confusing results. On the contrary, low frequencies are causing difficulties in identifying the triggering event or a lack of an adequate number of data for the mentioned self-learning algorithm.

During the system planning, once the questions to be answered are clarified, it is necessary to decide the physical entities to measure, define the positions where they should be monitored and select the most appropriate instruments to achieve the best compromise between results and cost-effectiveness.

2.1.2. Monitoring of shallow geotechnical structures

This term indicates the structures, which have a strong interaction with the natural materials at shallow depth, like for example proper walls, diaphragm walls, superficial or deep foundations, piles, bulkheads and wells.

In this situation, the aim of the monitoring is the control of the correspondence between the design hypotheses and the effective response of the structures during the construction works. Consequently, it should be easier to select appropriately the physical entities to monitor and their expected magnitude. It would be a good rule that the designers indicate the best position of instrumentations and the expected magnitude values or the variability range. This would permit the correct application of the observational method [17]. In this way, the monitoring system designer could identify the technological solution that better fit the issue. They can also be able to define the alert thresholds to activate an early warning system procedure.

Frequently, during the monitoring, it is determinant to transfer the sensors data rapidly to the technician responsible for the result control and interpretation. The presence of thresholds and the necessity of an automated system for data collection is of fundamental importance when the number and typology of installed instrumentation make impossible for the responsible to control and evaluate all the results at once. It should not be forgotten that instruments offer important indications about what happens to structures or around them, but these indications are useless if the person responsible for decision does not receive and analyse them. In these situations, the huge number of installed sensors gives a warranty of a more extensive control but also introduces the problem of choosing useful and meaningful information in each construction phase. The availability of data collected in a relational database offers the opportunity to realize a pre-screening of received data and a systematic and automatic control of all the defined thresholds, drawing the attention of the person in charge on the single potentially critical situations. However, the use of such "smart" data management platforms has the disadvantage of being generally outside the site areas and it requires an immediate transfer of measures to remote servers. Nowadays, with the global connection system and mobile phone equipment, it does not seem to be a problem anymore. Data traffic on web platforms has reached such a volume, considered usual, that even sending numerous data from monitoring systems is now a small task. The only cases where the technician should pay attention are the environments disturbed by electromagnetic waves and the places where there is a frequent temporary or systematic loss of the telephone signal. In this last case, it is necessary to use transceivers on reserved frequencies, such as those dedicated to emergencies. The need for data transmission adds a criticality to the entire monitoring process and it is appropriate that the data logger has a local storage and backup of the data, also for a limited period. This would preserve the registered raw data to be lost. In particularly complex sites, where there are a lot of instruments, there is often a preliminary level or radio transmission of the signals of some sensors to neighbouring data loggers and a second level of transmission to the elaboration centre. To achieve the first step, it is possible to use a Wi-Fi low consumption intranet connection, which reduces the need of long and tangled cable connections.

2.1.3. Monitoring of underground geotechnical structures

This term indicates the structures which have a strong interaction with the natural materials and which develops mostly in the underground, like deep tunnels, underground tunnels, mines, underground deposits, etc.

In these applications, the monitoring has the same finality of the one described in the previous paragraph, with the addition that it is determinant to monitor the behaviour of the natural contour materials at a certain distance from the excavation. This need is often linked to the verification of the design hypothesis about the mechanical and/or hydraulic behaviour of the natural material around the excavation, which for these environments is the most significant element ([12]).

In this specific monitoring, the requirements described in the previous paragraph merges together with some of those relating to the monitoring of natural phenomena. The activation of the monitoring system at the contour of the structure should be performed in advance of the beginning of works. This is fundamental to define the basic behaviour of the area, which will be "modified" during its construction. In many cases, it may be necessary to monitor existing structures that could be damaged and/or modified during construction work. Such monitoring will also have the purpose of demonstrating, where necessary, the failure or irreparable damage to property being recriminated by the owners of the nearby facilities.

In this monitoring category, additional requirements may be introduced, such as acoustic and vibration monitoring during excavation, and environmental monitoring within the underground cavities to ensure the maintenance of a healthy environments for workers. In case of vibration monitoring, it is necessary to underline that the frequency of acquisitions required and the amount of data would limit the use of the traditional data logger used in geotechnical monitoring. This article will not cover this type of monitoring, although being of secure interest in several occasions.

3. TRADITIONAL INSTRUMENTS TYPES

All the monitoring instruments are designed with the goal to measure directly or indirectly physical entities. Errors and uncertainties characterize each measure. It is important to define which are the characteristics related to uncertainties and errors of each measure, in order to select the most appropriate instrumentation for the specific purpose. The instrumentations should conform to the environment to measure: this means that the tools should theoretically read the parameters of interest and avoid disturbing them. In the case of inclinometer for example, this topic means that the casing and the mortar should have the same deformability of the soil with which they are in contact. Another characteristic is the accuracy, which is defined as the description of systematic errors, as this cause a difference between a result and a "true" value [21]. It is generally possible to evaluate the accuracy during the calibration procedure, when comparing the value measured by the sensor with the "real" value, recorded using an instrument with a known and verified accuracy. It is usually indicated as a percentage of the full scale (% FS). Another parameter is the precision, which is the description of random errors, a measure of statistical variability [21]. This value is a synonymous of the repeatability and the correct number of decimal digits after the comma indicates it. Resolution is the term that indicates the minimal scale division of the instrument. In the case of digital instrumentations, the maximum resolution is the unit variation of the last number in the display (or the division between the full scale and the number of bit). The sensitivity is the minimum magnitude of input signal required to produce a specified output. A high sensitivity does not imply a high accuracy or precision. Linearity indicates how much the values provided by the instruments are directly proportional to the measured quantity, while the hysteresis regards the measurement of a quantity, which varies cyclically: in some cases, the measure of the same physical quantity depends on the fact that the magnitude is growing or decreasing. The difference between the growing and the decreasing curves is the hysteresis. Finally, noise is the term which indicates the random variation of measures due to external factors: this creates a lack of precision and accuracy. If the noise is excessive, could mask the smallest variation of the measured physical entity.

The definition of errors is the difference between the measured and the real value: mathematically is equal to accuracy. Errors could have many different causes and it is possible to define them as accidental, systematic, environmental, of conformity, of observation and of sampling.

This chapter will quickly present the various types of tools available today for geotechnical monitoring. The organization of the chapter is based on the physical quantities to measure. The available tools will be indicated.

3.1. Measure of water level (pore pressure)

The measure of water level is of fundamental importance in many monitoring cases, thanks to the fact that water modifies the effective stresses in soil and is often the triggering factor of landslides. A piezometer is a device used to measure static pore pressure (in particular the piezometric head) of groundwater at a specific point ([8]) and it is mainly of two families.

3.1.1. Open standpipe piezometers

Open standpipe piezometers consist of a riser pipe and filter tip, backfilled with sand, and a bentonite seal above. Pore water flows into the standpipe to reach a pressure equilibrium. Water level inside the pipe represents the pore water pressure in the soil, which is possible to know reading an indicator.

3.1.2. Casagrande piezometers

A Casagrande piezometer usually has a solid casing down to the whole depth of the borehole and a screened casing within the area where it is necessary to measure the pore pressure. The casing is sealed with clay, bentonite or concrete to prevent the contamination of the groundwater level with surface water or other aquifer levels. If the aquifer is unconfined, the water level registered would not be exactly coincident with the water table, in particular when the vertical component of flow velocity is significant. If artesian conditions confine the aquifer, water level indicates the pressure in the aquifer, but not necessarily the water table [13].

3.1.3. Electrical pression transducers

Pressure gauges like vibrating-wire, pneumatic or strain gauge convert pore pressure into an electrical signal. These piezometers are isolated inside a single aquifer and cabled to the surface where there is a data logger or portable readout unit. Each sensor has its own cable. Compared with open standpipe and Casagrande piezometers, this kind of instruments have a quicker response and allow for automated reading.

3.2. Measure of deformations

3.2.4. Extensometers and crack meters: optical, mechanical and electrical

Crack meters are designed to monitor fractures in structures and the change of discontinuity aperture in rock masses. They can be optical, mechanical and electrical. The first two typologies are manual, while the third one is automated by means of potentiometer or vibrating wire transducers. The optical crack meter consists of two plastic elements bound to the end of the fracture and parallel to each other. They allow the measurement of the displacements in two perpendicular directions. The mechanical crack meter is mono-axial or triaxle. In the first case, it consists of a steel rod that is installed orthogonal to the direction of the fracture, bound to one end and free to move on the other. It is possible to measure the opening of the crack using a comparator. The triaxle mechanical crack meter has two distinct bodies: a square section prism and an external frame with three comparators with which it is possible to measure deformations along three orthogonal axes [10]. Finally, the electrical typology consists of a linear displacement transducer provided with two anchors fixed to the sides of the crack. It can be triaxle as well, if provided with an adequate number of linear and rotary transducers that measure the movements along the three directions.

3.2.5. Multipoint Borehole Extensometers

Multipoint borehole extensometers are usually used in underground excavation to monitor the radial deformations inside the rock mass. They have three main components: the head, integrated with displacement transducers, the anchors and the bases. The installation is usually inside radial perforations drilled in the plane of the tunnel section. Rods are anchored at different known reference points inside the hole through cementation, while the head is placed outside the hole. If deformations occur, the rods will slide through the head of the instrument, returning the magnitude of the displacement.

3.2.6. Manual inclinometers and In Place Inclinometers

Inclinometers are instruments used to monitor geotechnical structures and slopes in order to study subsoil deformations along the depth and consequently find the position of potential sliding plane. This kind of instrument returns the distribution of displacements perpendicular to the vertical by measuring rotations at specified positions. The system is constituted by a deformable inclinometric pipe provided with two pairs of guides, which are rigidly coupled to a survey hole or to a structure, and a probe constituted by a cylindrical body with two carts to slide along the guides of the tube, preserving the azimuth. A transportable control unit, placed on the ground, read the sensor two times for each depth along two orthogonal planes to reconstruct the resulting vector. To improve the quality of the results and apply a hardware filter, two conjugate measures (0° and 180°) are performed for each pair of guides. The displacement along the two directions is calculated using trigonometric formulas, starting from the knowledge of angles and step of measures. In Place Inclinometer (IPI) uses the same principles of manual inclinometer but it is automated and fixed at a specified depth. It only provides the tilt angle at that position and it requires to previously know where the displacement is to be expected. It is difficult to interpret the relevance and significance of this kind of results, which are not representative of the situation along the vertical borehole. In both cases, there are two main families of sensors, which are based on MEMS (Micro Electro Mechanical System) or Servo Accelerometers. Servo Accelerometers have a great sensibility, accuracy and precision, while the main issue is the cost of the sensors. They are suggested when it is necessary to monitor very little deformations with great accuracy. MEMS are much cheaper, but less sensitive, precise and accurate than the previous one. Nevertheless, with the latest advances in technology, they are suitable for the inclinometric field, expecially when kept in a single location (such as for in place inclinometers).

3.2.7. Settlement gauges

Settlement gauges are used to monitor soil settlements and deformations by measuring the variations of distance between two or more points in one direction. The principle of operation is based on the installation of aluminium or fiberglass rods in hollow boreholes with one end solidified at a fixed point and the other end passing through a ring fixed at the surface where there is an electrical transducer. In the case of displacements, the rod slides inside the ring and returns the pitch variation between the points.

3.2.8. Differential extensometers for the measure of settlements

The differential extensometers designed to measure the settlements along a vertical pipe have an operating principle based on the installation of a plastic pipe with metal rings at a constant distance within a perforation. The pipe is equipped with a guide to allow the insertion of the measuring system, which is constituted by a probe capable of detecting the position of the rings. Through these data, it is possible to know the relative movements between the points of the ground where rings are present.

3.2.9. Extensometers for concrete or steel

One-dimensional or triaxle extensometers are able to monitor the deformations of geotechnical structures like diaphragms, foundations, ribs. These tools can be drowned in concrete or welded on reinforcements. It is possible to estimate the load acting on the monitored element by knowing the deformation, the constitutive laws and the dimensional characteristics. There are two main kinds of extensometers. They differ according to the operating principle. The first one is the Extensometric Bridge, which measures instrument looks like a steel section bar with a square cross section, instrumented on each side with a Wheatstone bridge extensometer. The measure of deformations is related to the strain resistance variation. The second one is the vibrating wire transducer. It looks like a hollow tube, fitted inside a steel wire bound to the ends, and an electromagnet placed in the middle that can swing the cable. When a deformation occurs, the length of the steel wire varies and the frequency of vibration varies accordingly. The deformation is measured indirectly evaluating the variation of the wire vibration.

3.2.10. Clinometers

Clinometers can automatically monitor the rotations of structures or terrains in a single location. This kind of instrumentation could be mono-axial or bi-axial and it is placed on the construction by means of special adjustable support. The sensor is a MEMS or an electrolytic cell and it is able to measure the tilt along the horizontal plane, perpendicular to gravity. They have a good precision and low cost, but also a considerable temperature sensitivity, which can be corrected with a factory generated thermal calibration procedure.

3.2.11. Automatic inclinometers

During the last few years, some private companies and research groups have developed new automatic inclinometer devices. They will be analysed in detail in Chapter 4.

3.3. Measure of stresses

The monitoring of the stresses during construction and exercise phases is a fundamental aspect when validating the design assumptions and define the alarm thresholds. Instruments used for this kind of monitoring are generally load and pressure cell.

3.3.12. Load cell

Load cell measures the load applied to an object. The more common typology is the electrical one, constituted by a metal body (stainless steel or aluminium) to which it is possible to apply some extensometers. The number of extensometers is usually four in the configuration of Wheatstone bridge or vibrating wire sensors. It is possible to measure indirectly the force applied to the instrument by knowing the variation of electrical resistance measured in the extensometers.

3.3.13. Pressure cell

Pressure cells record the distribution, intensity and direction of total pressures. They are classified as hydraulic or membrane cells, according to the principles of operation. The first type consists of two circular or rectangular plates, welded together with a chamber. Oil fills this one, which is connected to a pressure transducer. The flexible membrane cell evaluates the instrument stresses by reading the deflection. The membrane is equipped with an electric resistance or a vibrating wire transducer. Depending on the typology selected, there are advantages and disadvantages in terms of precision, signal stability and temperature sensitivity.

4. INNOVATIVE INSTRUMENTS: CONCEPTS AND APPLICATIONS

Over the last few years, the application of monitoring to geotechnical works has gained greater development and importance. The introduction of design based on reliability (Reliability Based Design), made with Eurocodes, has given a further boost to the observational approach. This has led to an increasing number of pressing demands for the verification of works during construction and exercise phases by the public and private contractors.

These requests led to a longer period and increasing frequency of monitoring, which determined an increase of the economic amounts to allocate for it, when accounting the works. In many cases, it has also been verified that due to the greater accuracy and proper planning of the monitoring systems, it has been achieved the dual purpose of providing assurance to the designer and the contractors and to reduce the total cost of construction. The advent of innovative measuring instruments has enabled more complete and immediate answer from the outcomes of monitoring systems. The combination of different types of traditional sensors is often the base of this kind of instrumentation. In addition, geotechnical sensors have undergone considerable developments in the electronics and electromagnetic fields, regarding the reliability, durability and accuracy. All this happened as many sensors have been adapted to the geotechnical field as a derivation from other broader and more profitable market, such as automotive and consumer electronics.

In the field of indirect monitoring, in addition to the classic use of automated topographic instruments, there are photogrammetry, laser scanner and ground radar techniques, which have expanded and made more economical the measure of surface displacement over large areas.

4.1. Direct measures

The requirements outlined above have inspired the innovative tools introduced in the market in the last few years. They generally consist on the integration of various sensors to return a complete and reliable measurement framework. The multiplicity of measure and technologies introduced, enable high automation of data collection and a more reliable validation of results. This chapter briefly lists and describes some of the innovative tools most used in recent years.

4.1.1. Differential Monitoring of Stability (DMS)

Differential Monitoring of Stability (DMS) is an innovative-patented tool produced by CSG S.r.l. (IT). This instrument can be preassembled and installed in site forming an instrumented column, like a spiral cord, connecting the required number of modules ([2]) and can monitor in near-real time landslide and geotechnical structures. Each module could contain a 2D MEMS, piezometer, thermometer or extensometer sensors and the electronic board. Flexible joints link the modules preserving the azimuth. Control unit automatically reads data from DMS columns through RS485 protocol and it can send warnings to the responsible of monitoring. A proprietary stand-alone or online software calculates and represents the results, using trigonometry for the evaluation of displacement.

4.1.2. Modular Underground Monitoring System (MUMS)

Modular Underground Monitoring System (MUMS) is an innovative-patented tool produced by ASE S.r.l. (IT) ([3]). The instrumentation is an array of different nodes (Link) linked by a quadrupole electrical and an aramid fibre cables that can be equipped with 3D MEMS, electrolytic cell, piezometer, thermometer sensors and electronic board. Chains are custom made, preassembled, with the distance between sensors that could vary along the same vertical. Control unit automatically queries data through RS485 protocol at specified frequency that could change during monitoring. The ideal applications are the monitoring of landslides, settlements and geotechnical structures, like dams and underground excavations. Raw data are processed at the elaboration centre by a proprietary software and algorithm, based on the quaternion algorithm ([22]) for the evaluation of displacement. An interactive web-platform represents the results through multi-parametric graphs. The system can automatically send alert and alarm messages.

4.1.3. Shape Accel Array (SAA)

Shape Accel Array (SAA) is a patented geotechnical instrumentation device developed by Rensselaer Polytechnic Institute (USA) and Measurand Inc (CA). The instrumentation is an array of jointed flexible tube equipped with MEMS sensors, spaced 200, 305 or 500 mm ([7]). Each tube has the same azimuth and displacements are evaluated using trigonometry and the known geometry of the array. Control unit automatically queries sensors in near-real time and periodically upload results on a web-platform. The system could send a warning message to an engineer via e-mail or text message if thresholds are exceeded.

4.1.4. AIS

AIS system is a mechanized inclinometer designed by CNR-IRPI of Turin (IT) to operate by remote control of a unit microprocessor ([11]). The system is composed by a 2D servo accelerometer or MEMS sensor, an electric motor to drive the probe up and down inside the manual inclinometer casing, a load cell for the probe anti-embedding control and finally an encoder, which measures the position of the probe inside the borehole. The software is able to send alarms if slope movements exceeds a thresholds.

4.2. Indirect measures - remote sensing

Among the innovative tools used to monitor natural phenomena and geotechnical surface structures, it is necessary to consider also remotely based systems. Although limited to surface displacement measures, these systems are very useful for the control of rather large areas or structures with significant development, such as viaduct located on potentially unstable areas. The use of these medium-scale control technologies increases the effectiveness of monitoring by expanding the results obtained with direct measures to larger areas. This is particularly useful in the study of the evolution of natural phenomena, such as landslides, where the heterogeneity of the geomorphological, geotechnical and hydrological characteristics causes a substantial variation in the dynamics of the events. These tools become crucial in cases of real time or near real-time monitoring of recent activation instability phenomena, given the rapid installation and immediate operability of most of these systems, where it is possible to integrate them with automatic digital image correlations techniques.

4.2.5. Mechanized topographic survey (Total Station)

The mechanized topographic survey can track the shift of interest points along time. The system is based on a total station equipped with robotic automatic collimation on reflective prisms installed at the points of interest. Through the collimation of the prisms, it is possible to return their position and displacement over time.

4.2.6. Laser Scanner

Laser scanners are instrumentations able to reproduce three-dimensional models of objects detected by generating a point cloud ([14]). Each point has the information about distance, horizontal and vertical angles with respect to the instrument. Comparing recreated models at different times it is possible to know the deformations eventually occurred.

4.2.7. Automatic terrestrial photogrammetry

Photogrammetry is a prominent technique that works without direct contact with the object. It is based on the use of couples of photos, made through calibrated camera. The spatial position of the representative points of the detected object is obtained by using two central perspectives of the same object from two projection centres (as in paper [6], [9], [18], [19] and [20]).

4.2.8. Terrestrial interferometry (GB-SAR)

Terrestrial interferometry (GB-SAR) is a technique of remote sensing surface deformations concerning large portions of territory, such as slopes or structures ([1], [5] and [16]). The technique is based on the correlation of different radar images, generated and acquired through a device equipped with transmission and reception antennas. This device moves along a track installed orthogonally with respect to the direction in which it is necessary to monitor the movements. The result is a picture consisting of a quantity of pixels that is closely related to the distance between the radar and the monitored scenario. It is possible to process a map of shifts along the instrument line of sight by comparing the phase differences of each pixel between two captured images at different times.

4.2.9. InfraRed Thermography (IRT)

InfraRed Thermography (IRT) is a non-destructive technique applied to the monitoring of civil structures and natural slopes/rock masses ([15]). It is based on a survey of thermal energy emitted by monitored object, through thermocouples. Using this technique, it is possible to describe the distribution of water circulation, within granular or rocky soils, and the presence of discontinuity in the surface layers. In the monitoring of civil works, thermography is used to detect any water infiltration, injury or anomaly in the structure.

5. CONCLUDING REMARKS

The advent of multi-functional data collection platforms, together with the robust and reliable global networking, has enabled the transfer of large amounts of data in real time (or with minimal delay), their automatic analysis and storage in large relational databases. This made possible the automatic and near-real time comparison of various types of measurements derived from different technologies, greatly improving the validation of data and, consequently, the reliability of results. In addition, the availability of longer observation periods with higher frequency of acquisitions, if compared with traditional measurements, permitted the creation of much larger sample populations, allowing more reliable statistical processing. This enabled the reach of excellent results regarding reliability and meaning of measures, sometimes slightly sacrificing the quality of sensors, in favour of the diffusion, and the lower cost of innovative solutions. This holds true because monitoring measures do not require extraordinary precision or high accuracy, since they are generally based on differential measures from an initial reference reading.

The modern geotechnical engineer should take advantage of the innovations that became available in the recent field of monitoring instrumentation and of automated data recording and display, for several reasons. At first, the availability of such recordings, when scheduled during the design phase, enables the designer to increase the reliability of the geotechnical or geomechanical parameters. This leads to the potential reduction of the design factors to be used accordingly to the Eurocodes. Again, the application of the observational method, supported by an increased number of measured parameters that can be easily related and controlled, frequently leads to a potential reduction of costs even during the construction phases. Last, but not least, the availability of data recorded before, throught and sometimes after the entire construction phase safeguards both, the designer and the owner, against potential complaints and expensive legal issues.

Recalling all the above described considerations, geotechnical monitoring should became a standard and peculiar design instrument, to be considered mandatory and commensurate to the complexity of the assignment. Design costs related to geotechnical and structural monitoring should be adequately sized by the designer, according to the specific uncertainties involved in the project and, being an instrument that increases the construction safety, should be excluded from any auction rebate in tenders.

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